AD NUMBER
AD834707
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; MAR 1968. Other requests shall be referred to Air Force Materials Laboratory, Wright-Patterson AFB, OH 45433. This document contains export-controlled technical data.**
AUTHORITY
USAFML ltr, 29 Mar 1972

AFML-TR-66-324
Part II

A STUDY OF THE STRAIN-AGE CRACK SENSITIVITY OF RENE' 41

W. P. Hughes
T. F. Berry
R. E. Yount

General Electric Company

TECHNICAL REPORT AFML-TR-66-324, PART II

March, 1968

~~This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Metals and Ceramics Division (MAM), Air Force Materials Laboratory, Wright-Patterson AFB, Ohio 45433.~~

Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

208

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

CFSTI WHITE SECTION ☐
DDC BUFF SECTION ☑
UNANNOUNCED ☐
JUSTIFICATION

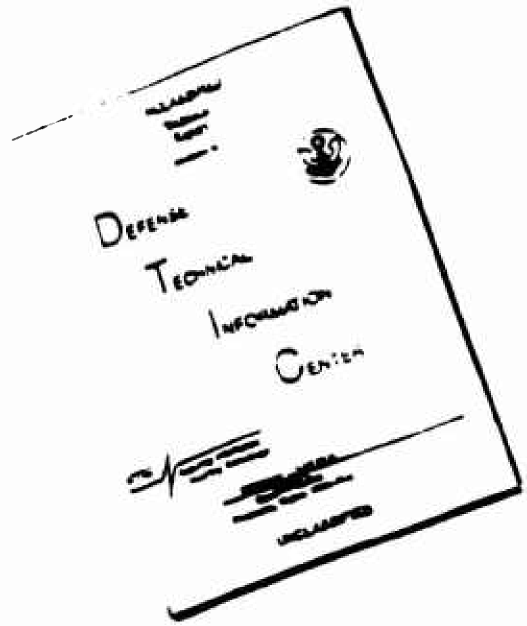
BY
DISTRIBUTION/AVAILABILITY CODES

DIST.	AVAIL. and/or SPECIAL
2	

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Metals and Ceramics Division (MAM), Air Force Materials Laboratory, Wright-Patterson AFB, Ohio 45433.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specified document.

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

A STUDY OF THE STRAIN-AGE
CRACK SENSITIVITY OF RENE' 41

W. P. Hughes

T. F. Berry

R. E. Yount

FOREWORD

This report was prepared by the Materials Development Laboratory of the Aircraft Engine Technology Division of the General Electric Company. The project was administered under the direction of the Air Force Materials Laboratory, Metals and Ceramics Division, with Mr. Robert E. Bowman (MAMP) serving as Project Engineer. The work was conducted under USAF Contract AF33(615)-2717, Project Number 7351, "Metallic Materials", Task Number 735102, "Welding and Brazing of Metals".

The report describes the results of research conducted during the period 1 August, 1966 and 15 February, 1968. The contract was managed for the General Electric Company by Mr. R. E. Yount under the direction of Mr. G. S. Hoppin, Manager, Metallurgical Process Development Sub-Operation. The principal investigators were Messrs. T. F. Berry and W. P. Hughes. Mr. J. F. Barker assisted in interpretation of results and microstructures. This manuscript was released by the authors May, 1968 for publication.

This technical report has been reviewed and is approved.

I Perlmutter

I. PERLMUTTER
Chief, Metals Branch
Metals and Ceramics Division
Air Force Materials Laboratory

ABSTRACT

A program of research work directed toward the study of strain-age crack sensitivity of precipitation hardened nickel base alloys in sheet form was conducted and is described. The alloy chosen for study was Rene' 41. The primary objectives of this study were:

1) To perfect and use a screening test to quantitatively evaluate those factors which contribute to the strain-age cracking mechanism.

2) To subsequently use this information to improve material quality and/or welding and heat treatment procedures to minimize or eliminate the occurrence of strain-age cracking in fabricated components of Rene' 41.

A post weld heat treating procedure was devised for a restrained circular welded patch test which defined the isothermal exposure times and temperatures in the aging range where strain-age cracking occurs. The limits of cracking established had the shape of the letter "C" and were subsequently referred to as "C-curves". C-curves developed were found to be useful in defining the minimum heating rate which could be used to heat a restrained weldment to the solution treatment temperature without the occurrence of strain-age cracking.

Two testing procedures were developed, a constant load and a constant strain, using "Gleeble" equipment (a time-temperature-stress device developed by Doctors Nippes and Savage of Rensselaer Polytechnic Institute). These procedures and the isothermally heat treated patch tests were capable

of measuring differences in the strain-age cracking sensitivity of different heats of Rene' 41.

Using the above testing procedures, it was found that a preweld overaging heat treatment eliminated the occurrence of strain-age cracking in the most crack-prone heat of 0.060 inch Rene' 41 sheet studied. Furthermore, it was shown that elevated temperature tensile and stress rupture properties of overaged material can be restored to normal values by a solution and aging treatment.

In those cases where overaging prior to welding cannot be used, the following factors were found to reduce the strain-age crack sensitivity of Rene' 41.

1) Maintaining the iron, silicon, sulfur, and manganese content at low compositional levels.

2) Maintaining a finer grain size in annealed sheet than ASTM grain size of 3.

CONTENTS

CONTENTS (Cont'd)

CONTENTS (Cont'd)

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

TABLES

TABLES (Cont'd)

TABLES (Cont'd)

I. INTRODUCTION

The demand of the aerospace industry for high strength - high temperature resistant alloys in sheet form prompted the development of the precipitation hardened nickel-base sheet alloys such as Inconel X, Rene' 41, Waspalloy, et al. The availability of these alloys as commercial products made possible the design of lighter weight heat resistant welded structures. Superficial welding studies initially performed on these alloys indicated that welding was a satisfactory fabrication process for these alloys. Unfortunately, when some of the first complex fabrications of these alloys were made, they were so designed that the welds were subjected to significantly larger amounts of restraint than had been encountered in laboratory testing, and cracking occurred during the post weld heat treatment of the parts. The cracks which occurred were predominantly located in the heat affected zone near the weld fusion line. This type of cracking has been commonly referred to as strain-age cracking.

Because of this cracking problem, the use of strain-age cracking susceptible alloys such as Rene' 41 in highly restrained fabrications has generally been avoided. The design requirements for such structures have been scrutinized closely and in many cases other less crack sensitive but weaker materials have been used. In other welded components where the superior high temperature strength of alloys such as Rene' 41 was considered absolutely essential, success in component fabrication has been obtained only by "cut and try" procedures in welding, heat treatment, and repair welding, with the generation of a considerable amount of scrap. The application of such methods to the manufacture of welded components has caused the cost of these components to be considerably higher than would have been the case had sufficient information been available to either circumvent strain-age cracking or more drastically restrict its occurrence.

During the last ten years, a continual search has been conducted to devise a test procedure which would quantitatively measure the strain-age crack susceptibility of Rene' 41 and similar alloys in welded parts. The restrained circular patch test (to be more fully discussed in a later section) had been empirically established to give the most reliable quantitative data regarding this susceptibility. This test has been used by General Electric to evaluate the weldability of incoming heats of Rene' 41 and has assisted thereby in reducing the amount of weld cracking which occurred in highly restrained fabricated components. The test has also been useful in establishing both initial and repair welding procedures and heat treatments which have assisted in minimizing strain-age cracking.

The numerous "patch test" results and associated mechanical and chemical properties which have been obtained on various production heats of Rene' 41 have not indisputably disclosed the reason(s) for the varying degrees of susceptibility to strain-age cracking displayed by different heats or lots of material. Therefore, specification revision could not be instituted to aid in reducing the incidence of cracking. These empirically and expensively accumulated results indicated poignantly the desirability of perfecting a more quantitative test to predict strain-age weld crack susceptibility and the use of this test to study a controlled range of chemical composition, welding, and processing variables to determine those which are significant to the mechanism of strain-age cracking.

Briefly, the effort reported here had the following objectives:

1) To perfect and use a screening test to quantitatively evaluate these factors which contribute to strain age cracking in complex nickel base alloys.

2) To subsequently use this information to improve material quality and/or welding and heat treatment to minimize or eliminate the occurrence of strain-age cracking in fabricated components of Rene' 41.

The majority of results reported herein were generated during the last year and one half of a two and one half year contractual effort. During the first year's study[(1)*], the restrained circular patch test was used to demonstrate that the strain-age cracking phenomenon in Rene' 41 was dependent on a time-temperature-stress relationship. A specimen design and procedure using "Gleeble" equipment (a time-temperature-stress testing device developed by Nippes and Savage of RPI) was developed which was also capable of demonstrating a time-temperature-stress strain-age cracking relationship.

The time to strain-age cracking, when plotted versus temperature, produced a C-shaped curve. Both patch test and "Gleeble" test results produced C-curves which were relative indications of the sensitivity of different heats of Rene' 41 to strain-age cracking.

The above two test procedures were used to study the effects of chemical composition variations, mill processing and welding variables on

---

* Numbers in parentheses refer to items cited in References.

the sensitivity of Rene' 41 to strain-age cracking. The effect of low carbon (0.04%) on Rene' 41 crack sensitivity was also studied on a 5,000 pound heat.

During this effort, several significant conclusions were made. These were:

1) The amount of time to encounter strain-age cracking at any exposure temperature subsequent to welding appeared to be extremely dependent on the magnitude and state of stress imposed upon the heat affected zone of the weld.

2) The incidence and severity of strain-age cracking was a function of the cooling rate from a time-temperature exposure which produces a crack sensitive microstructure. Severity of cracking increased with increased cooling rate.

3) A stabilizing temperature of 1200°F can be used to replace the commonly used 1000°F during the post weld heat treatment of highly restrained Rene' 41 fabrications. This would permit a decrease in the time the part is exposed to the aging range, thereby, reducing the propensity for strain-age cracking. (This conclusion has been subsequently found not to be universally true. Weldments made of some large grained heats of Rene' 41 will strain-age crack at 1200°F).

4) Lowering the carbon content decreased the strain-age crack susceptibility of Rene' 41 within the low temperature range of 1300 to 1500°F. This range is believed to be the

the most critical range with respect to conventional heat treating practices.

5) The use of high purity raw materials during melting of Rene' 41 appeared to increase the resistance of Rene' 41 to strain-age cracking.

6) Increasing the thickness from 0.060 to 0.25 inches greatly increased sensitivity to strain-age cracking.

7) The strain-age crack sensitivity of Rene' 41 can be significantly reduced by using the electron beam welding process rather than the gas tungsten-arc process. However, the joint gaps required for electron beam welding are much less than for TIG welding.

8) Data obtained indicated that mechanical properties meeting the requirements of Rene' 41 specification can be maintained in low carbon (0.04%) Rene' 41 if appropriate increases are made in the titanium and aluminum content.

The first year's work established areas for further exploration and study to more fully define and verify these initial conclusions and to improve the techniques used for measuring strain-age cracking susceptibility. The subsequent study was divided into three overlapping phases, which are described below.

Phase I objectives were to modify and improve the testing procedures for measuring the strain-age crack sensitivity of precipitation hardened nickel base alloys. The crack susceptibility C-curve determined during the first year's effort represented cracking which occurred while isothermally aging and during cooling. There was no way to determine at which point cracking occurred. A more useful curve for comparing the effect on crack susceptibility of various factors and variables was a C-curve of cracking which occurred during heating. Cracking during heating to the solutioning temperature is the primary problem in post weld heat treatment of welded components.

The "Gleeble" testing previously conducted was obtained by loading welded specimens and maintaining a constant stress. These data were useful in determining strain-age crack sensitivity, but it was felt that the information would be more meaningful if the specimens were loaded and maintained at a constant strain and would be further improved if the biaxiality of the stresses imposed on the weld heat affected zone was increased.

The modified and improved patch test and "Gleeble" test procedures were to be used in Phase II to further document the effects on strain-age crack susceptibility of chemical composition, mill processing, base metal thickness, preweld base metal heat treatment, welding processes, and post weld heat treating environment.

Phase III was directed toward verification of the influencing factors discovered in Phase II by the procurement of a portion of a commercial heat to selected chemical and metallurgical requirements. The commercial heat would be subjected to the two weldability test procedures and compared to previously generated data.

Phase IV was established to determine if the testing procedures established using the Rene' 41 alloy were applicable to evaluating a new composition of a precipitation hardened nickel base sheet alloy. Rene' 63, a sheet alloy recently developed by General Electric, was selected for this phase.

II. SUMMARY AND CONCLUSIONS

A comprehensive study to establish those factors which affect the strain-age crack sensitivity of the precipitation hardened nickel base alloy Rene' 41 was conducted. An essential and significant portion of this study was to establish laboratory testing procedures which would measure these factors in a quantitative manner. The results of this study provided the following significant conclusions.

1) A restrained weld "patch" test post weld heat treating procedure (named Type III) was developed which quantitatively measured the time to initiate strain-age cracking occurring during an isothermal arrest in the aging temperature range for precipitation hardened nickel base alloys.

2) Two "Gleeble" test procedures, a constant strain and a constant load, were also developed which could measure differences in strain-age cracking sensitivity.

3) For quantitative measurement of differences in strain-age cracking susceptibility, the constant load "Gleeble" test procedure is the simplest and fastest testing procedure developed. Its simplicity makes it adaptable to other test equipments and would allow a more widespread usage of this procedure as a strain-age crack susceptibility test.

4) The C-curve using tha patch test Type III post weld heat treating procedure which defines the isothermal exposure areas which are subject to strain-age cracking, can be used to select the minimum heating rate to the solution treatment temperature for a highly restrained weldment to avoid strain-age cracking.

5) An overaging heat treatment prior to welding was, by far, the most effective method of reducing the incidence of strain-age cracking. The mechanical properties of overaged Rene' 41 can be completely restored by a post weld solution and aging heat treatment.

6) Rene' 41 with a mill annealed grain size of ASTM 3 to ASTM 8 was demonstrated to possess a greater resistance to strain-age cracking than Rene' 41 with a mill annealed grain size of ASTM 1.

7) The trend, established during the first year's effort, which indicated that Rene' 41 with low levels of iron, silicon, sulfur, and manganese had greater resistance to strain-age cracking. was confirmed.

8) Lowering the carbon content of Rene' 41 also increases the resistance to strain-age cracking. However, a method of restricting grain growth in low carbon Rene' 41 must be developed if the room temperature to 1400°F yield strength is to be retained at current specification levels.

9) The use of a vacuum during post weld heat treatment was found to increase the resistance of Rene' 41 to strain-age cracking at temperatures above 1500°F.

10) Welding processes which lower the residual stress level will reduce the sensitivity of the weldment to strain-age cracking.

III. EXPERIMENTAL PROCEDURE

A. PHASE I

During the first year's effort, testing procedures were developed to more quantitatively establish the validity of an hypothesis that cracking during the post weld heat treatment in the weld heat affected zone of nickel base superalloys is the result of interactions between residual welding, aging contraction, and thermal stresses acting upon the heat affected zone at a time when this zone was being or had been embrittled by metallurgical reactions. The testing procedures developed were the weld restrained circular patch test and a constant load test performed on the "Gleeble" equipment using the welded specimen with the weld transverse to the load.

The major objectives in Phase I of the current work were:

1) To refine the patch test post weld heat treating procedure so that it would predict critical heating rates to the solution temperature which are necessary to avoid cracking.
2) To evaluate a "Gleeble" testing procedure using a constant elongation rather than a constant load testing procedure.

It was expected that the data obtained would provide a more accurate duplication of results which would occur in restrained weldments during post weld heat treatment.

1.0 Modification of the Restrained Circular Weld Patch Testing Procedure

1.1 Background

The hypothesis proposed to describe the crack susceptibility characteristics of Rene' 41 (and other alloys subject to strain-age cracking) infers that strain-age cracking is dependent upon an interacting combination of time, temperature, and stress. The temperature-time dependence is related to the fact that strain-age cracking is dependent on an age-hardening metallurgical reaction involving a matrix precipitate, gamma prime, and grain boundary carbide reactions. The stress dependency is based upon the fact that strain-age cracking occurs only in restrained structures, where stresses from welding and subsequent heat treatment are sufficient to exceed the stress necessary for crack initiation and propagation. Welded fabrications in Rene' 41 free of restraint do not exhibit the severe, catastrophic heat affected zone fracturing characteristic of strain-age cracking. Thus, it would be expected that the cracking phenomena would have to occur in the aging temperature range and would be a function of the rate of aging which, in turn, is dependent on time, temperature, and stress. Since the aging rate at the lower temperature end of the aging range is relatively slow, the occurrence of strain-age cracking should approach asymptotically some lower temperature limit. Likewise, since stress due to restraint at the higher temperature end of the aging range is relatively low and precipitates formed at lower temperatures would dissolve, there should be a high temperature asymptotic. limit. At some themperature between the upper and lower asymptotic limits, there should be a minimum time, prior to which no cracking could be possible and beyond which cracking of some degree would be certain to occur.

It was the purpose of this phase of the investigation to identify the configuration of the curve which defines the upper and lower asymptotic limits and the minimum time for strain-age cracking to occur. This curve will be donoted herein as the crack susceptibility C-curve because of the presumed similarity of its shape to the letter "C". It was assumed throughout that the restraint stress variable was relatively conrtant due to the standardized geometry of the patch test assemblies and the uniform procedures used to fabricate them.

1.2 Welding Procedure

A sketch of the components of the restrained circular patch test assembly is presented in Figure 1. Fabrication proceeded by first welding the outer restraining sheet to the base plate and ultimately welding the center disk to the outer restraining sheet. The gap between the center disk and the outer restraining sheet prior to final welding was 0.040 to 0.045 inches. All patch test base plates and components were Rene' 41.

Patch test welding was performed semi-automatically using the gas tungsten-arc process with automatic filler wire feeding. Welding parameters for the center test weld were adjusted so as to achieve full penetration and controlled so that nearly identical parameters were used for each heat. Hastelloy W filler material was used during the fabrication of each patch test assembly. The sequence of fabricating a patch test assembly is shown in Figure 2. A detailed description of the welding procedure is given in Appendix A.

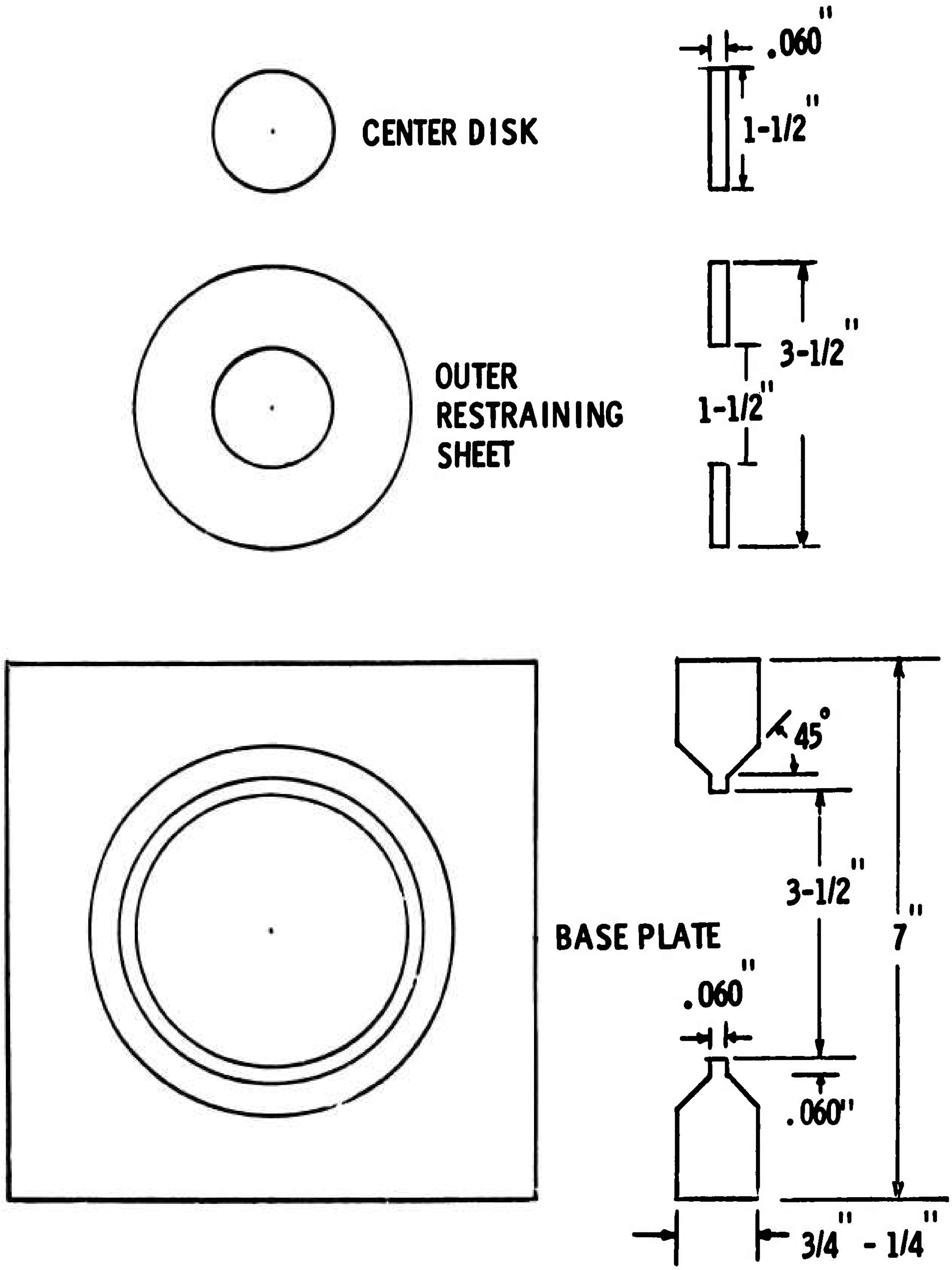
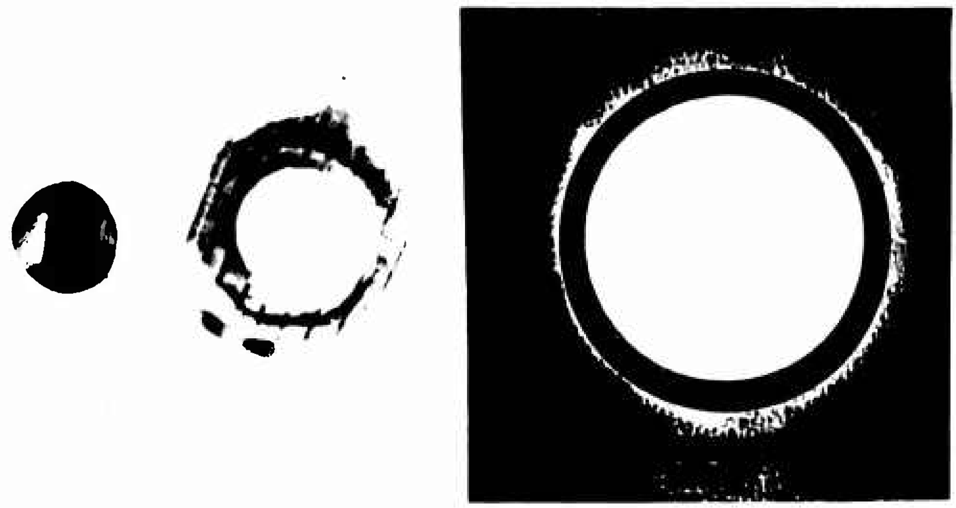


FIGURE 1. Sketch Showing Components of the Patch Test Assembly.



Stage 1 - The Separate Components of the Patch Test Assembly.

Stage 2 - The Outer Restraining Disk Welded to The Heavy Base Plate.

Stage 3 - The Completed Patch Test Assembly.

FIGURE 2. The Sequence Followed in Welding the Circular Patch Test Assembly.

1.3 Post Weld Heat Treating Procedure

The patch test assemblies were heat treated in air atmosphere, electric, box-type laboratory furnaces. The temperatures of the patch test assemblies during the heat treatment that followed initial fabrication were continuously monitored by thermocouples providing signals to a Honeywell Electronik #17 four pen recorder. Thermocouples were placed on the base plate and in the center of the sheet patch area permitting an accurate determination of the peak temperature, heating and cooling rates, and temperature differentials. Heating rates were controlled by transferring the patch test assembly from a furnace held at a stabilizing temperature of 1000°F into a furnace held at a predetermined superheat temperature and resetting the latter furnace to the temperature desired. Heating rates were thus varied by varying the amount of superheat in the second furnace. Where controlled cooling rates were required, the patch test assembly was sandwiched between two plates baffled to permit the circulation of compressed air. Cooling rates were controlled by varying the rate of air flow within the plates.

1.4 Crack Susceptibility C-Curve Determination

During the first year's work, the water quench, crack susceptibility C-curve was generated from the occurrence of cracks during a heat treatment which did not differentiate between cracking which occurred during isothermal exposure or during cooling. Though this curve provided a means for measuring the relative effects of various factors on strain-age crack susceptibility, it failed to isolate the effects that are specifically a function of the heating phase of a heat treatment. To isolate the time of cracking, it was necessary that cracking during cooling be eliminated. Cracking during cooling was caused by the high stresses which are generated by the large thermal gradient between the heavy base plate and thin patch center. This led to the selection of two methods of heat treatment which would eliminate the thermal gradient after isothermal exposure:

1) Furnace cooling from the isothermal aging temperature thus eliminating the stresses which arise from the difference in cooling rates in the thick and thin members of the weldment.
2) Solution heat treating after the isothermal aging exposure, thus eliminating the crack sensitive heat affected zone microstructure and relieving the residual welding stresses.

"C-curves" were developed using both of these post weld heat treating procedures.

It was found that the shape of the C-curve was determined largely by the method used to heat treat the patch test assembly after the isothermal aging temperature exposure. For the convenience of discussion, the various shapes of the curves were classified as follows:

a) Type I Crack Susceptibility C-Curve - generated by a two-step post weld heat treating procedure and water quenching from the isothermal aging temperature. This is shown schematically in the upper view of Figure 3.
b) Type II Crack Susceptibility C-Curve - generated by a two-step post weld heat treating procedure, furnace cooling from the isothermal aging temperature. This is shown schematically in the middle view of Figure 3.
c) Type III Crack Susceptibility C-Curve - generated by a three-

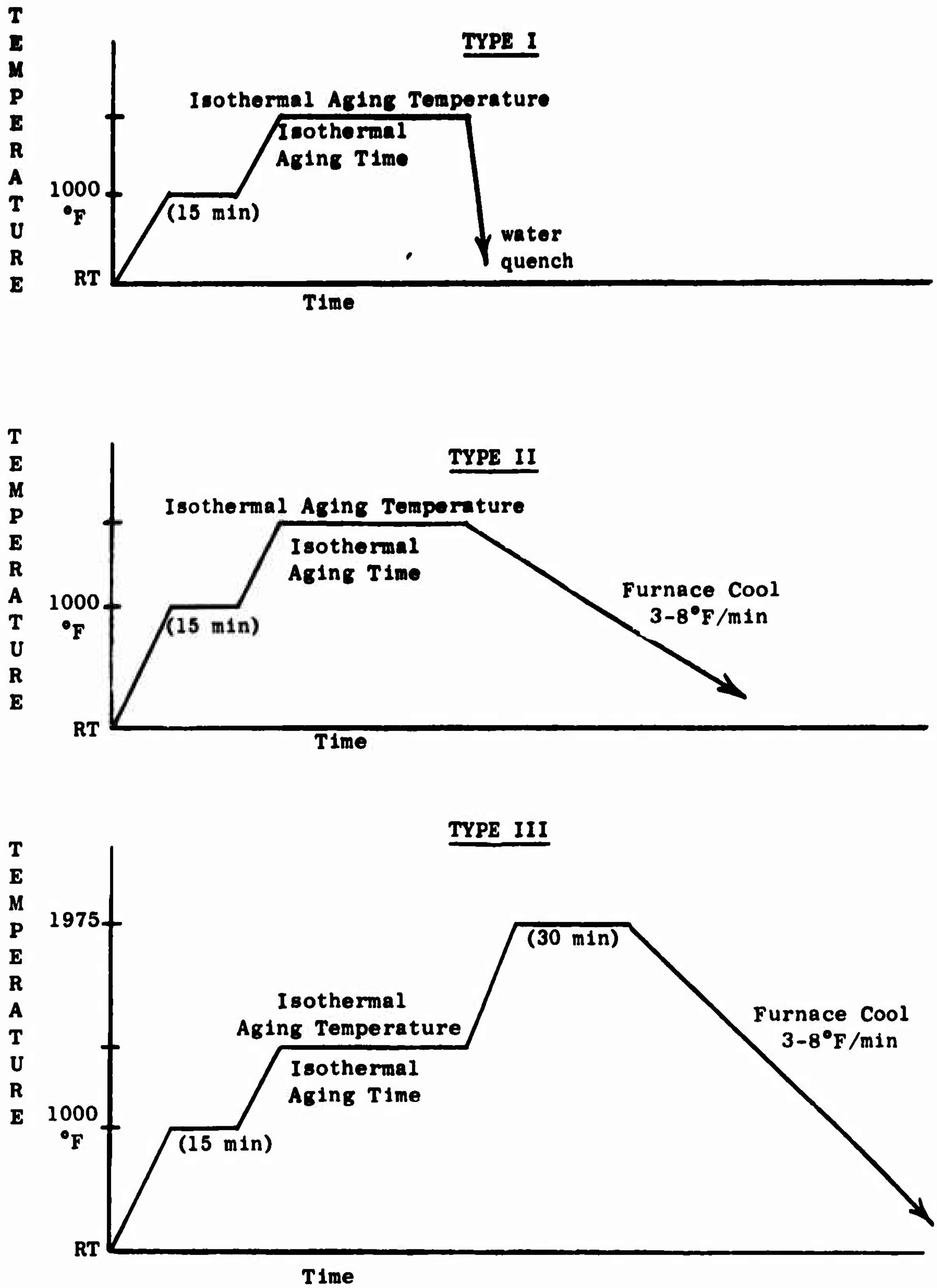


FIGURE 3. Schematic Illustration Showing The Heat Treating Procedure Used for Developing Types I, II, and III C-Curves.

step post weld heat treating procedure involving rapidly heating the patch to a 1975°F solution temperature, hold for 30 minutes, and furnace cool. This is shown schematically in the bottom view of Figure 3.

Each of these curves possess a certain degree of usefulness, and each has inherent limitations. The advantages of each class of C-curve will be discussed along with the presentation of C-curves developed for each class.

Type I Crack Susceptibility C-Curves

Type I C-curves were generated for Heats T3-8556 and T3-8565 during the first year's work[1] and are shown in Figures 4 and 5. They were observed to be similar in the following major aspects:

1) The upper and lower asymptotes were 1900°F and 1200°F, respectively.
2) The critical nose of the curve for both heats was within the temperature range 1700°F to 1850°F. The tip of the nose for T3-8556 occurred at 0.5 minutes and a tip of the nose for T3-8565 occurred at 1.3 minutes.
3) The shape of the curves between the asymptote limits was essentially the same exhibiting a high temperature nose and a low temperature nose. The low temperature nose occurred between 1275°F and 1375°F in each case.

The similarities of these two curves indicated that the crack susceptibility characteristics of Heats T3-8556 and T38565 were very similar as measured by the processing cycle used to generate the Type I C-curve (See

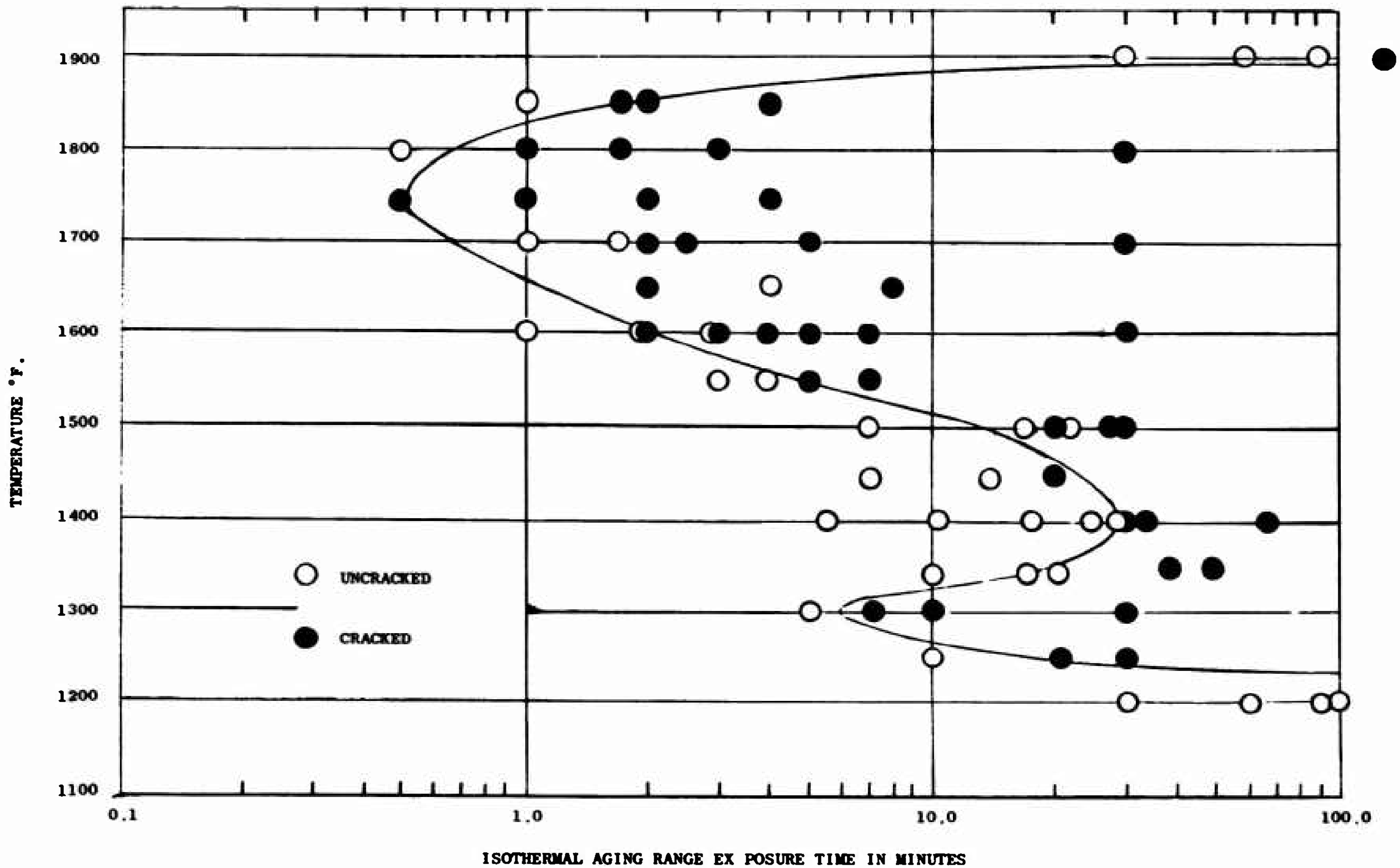


FIGURE 4. Crack Susceptibility C-Curve As Generated By The Patch Test Using The Type I Post Weld Heat Treating Procedure. Rene' 41 Heat T3-8556. Mill Annealed Prior To Welding.

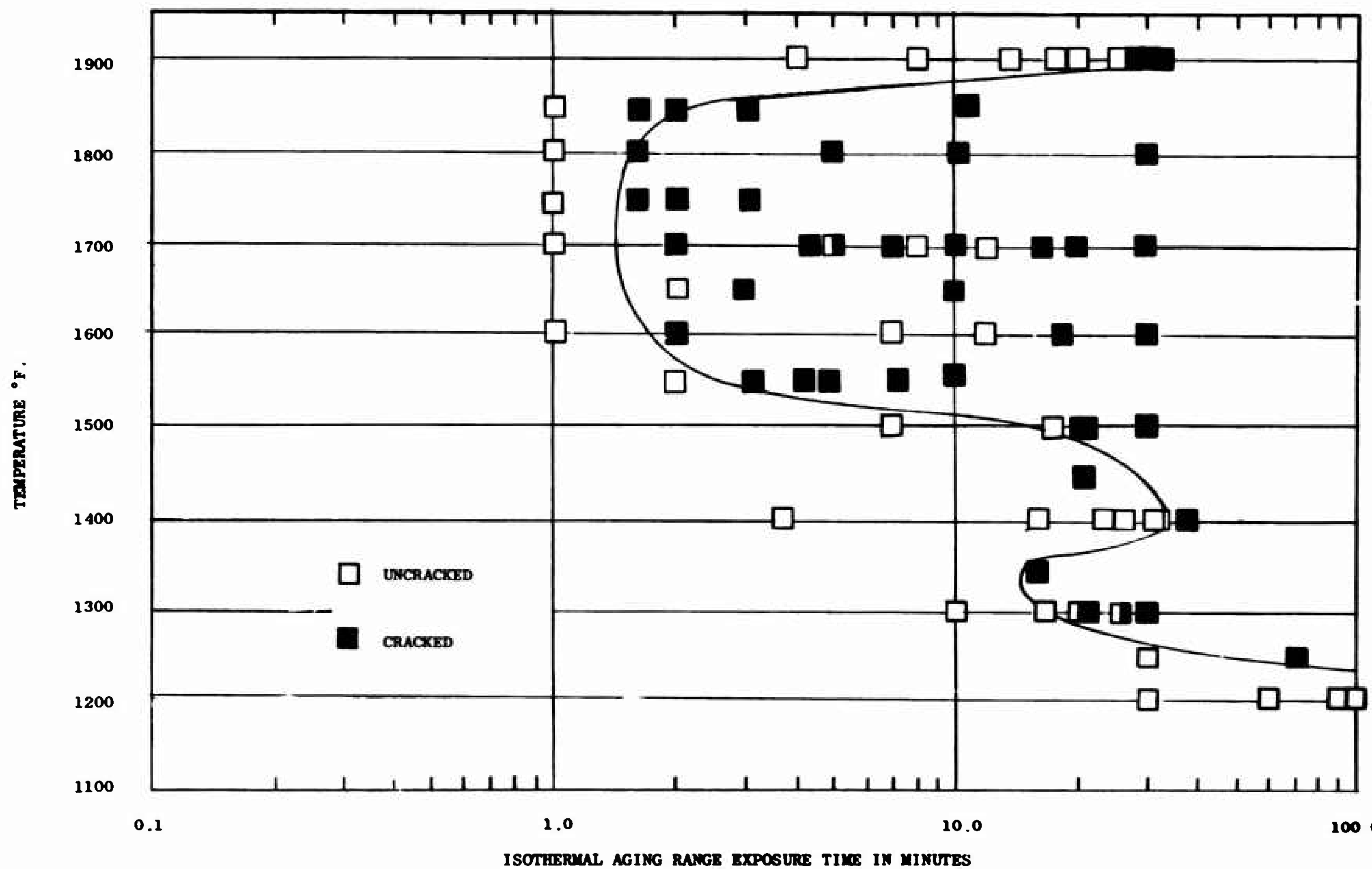


FIGURE 5. Crack Susceptibility C-Curve As Generated By The Patch Test Using The Type I Post Weld Heat Treating Procedure. Rene' 41 Heat T3-8565. Mill Annealed Prior To Welding.

Figure 3, upper view).

However, it was discovered, with a subsequent series of tests, that a portion of the cracking which was observed during development of the Type I C-curve occurred during the water quench from the isothermal age. Patch tests which were isothermally aged at 1800°F and quenched, at rates varying in severity from a water quench to a furnace cool, exhibited severe heat affected zone cracking during the rapid quenching operation and no cracking during the very slow cooling operation. These results are shown schematically in Figure 6. As a consequence, there was no way to identify whether or not the cracks observed from the Type I C-curve post weld heat treating procedure occurred while holding the patch test assembly at the isothermal aging temperature or during the water quenching from the isothermal aging temperature. Thus, to be certain that the nose of the C-curve defined the limiting time and temperature at which cracking would occur during heating at the solutioning temperature, was necessary to modify the post weld heat treating procedure to restrict the occurrence of cracking to the isothermal aging exposure time. The development of Types II and III C-curves was an attempt to do this.

Type II Crack Susceptibility C-Curves

Furnace cooling the patch test from the isothermal aging temperature (as shown in the middle view of Figure 3) eliminated the gross thermal gradient between the thick and thin members of the assembly, thereby greatly reduced the stresses that were developed with faster cooling rates. Data generated using this prodedure is plotted in Figure 7 for mill-

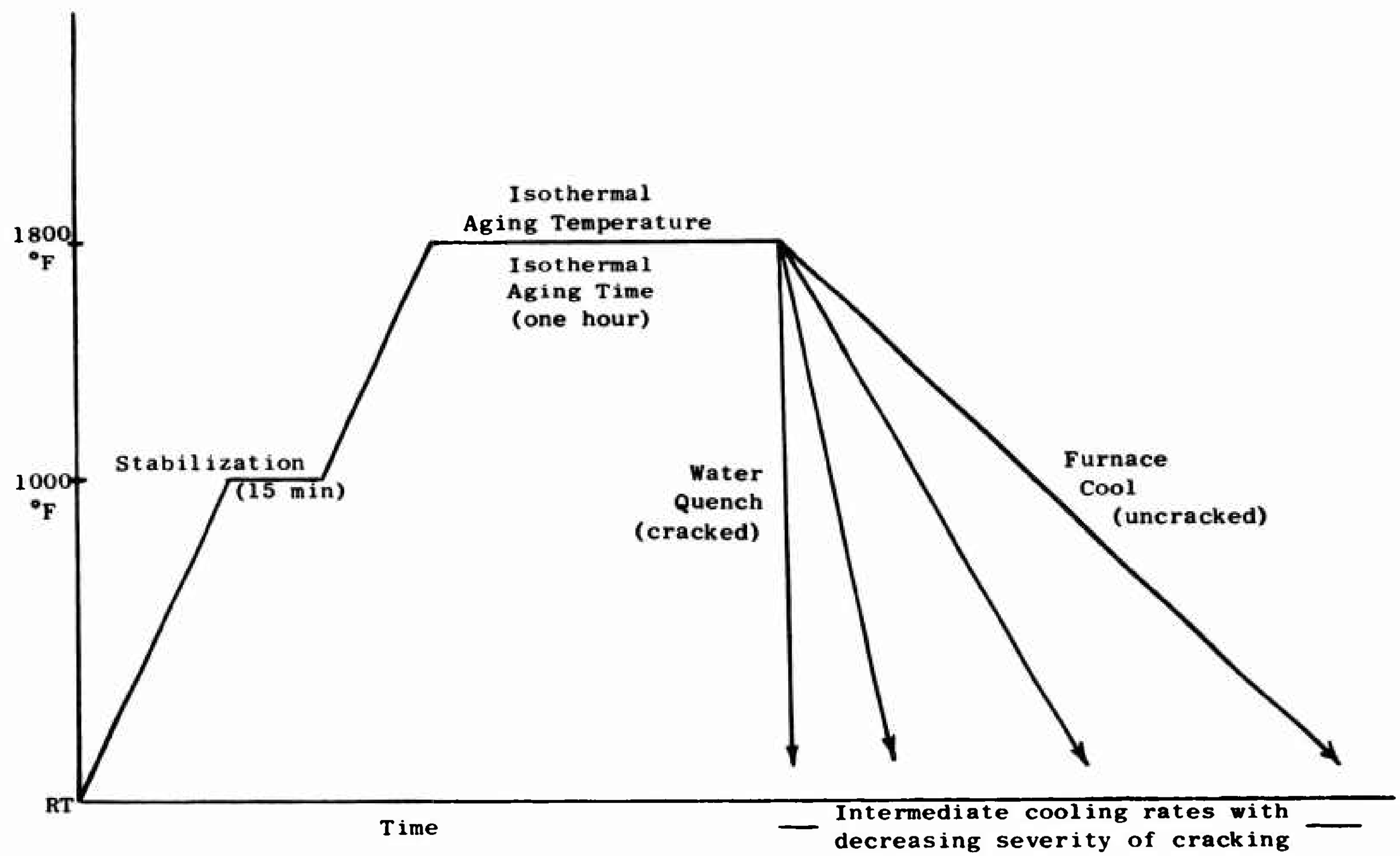


FIGURE 6. Crack Severity Resulting from Varying Cooling Rates From The Isothermal Aging Temperature.

annealed Heat T3-8556.

Figure 7 shows the absence of cracking above 1800°F and the occurrence of cracking at <u>all</u> times below 1600°F. There was no way to identify at what point in the heat treating cycle the strain-age cracking initiated since the slow cooling resulted in a long time exposure at aging temperatures.

Since the Type II heat treating procedure did not identify cracking which would occur during heating to the solutioning temperature it was discarded.

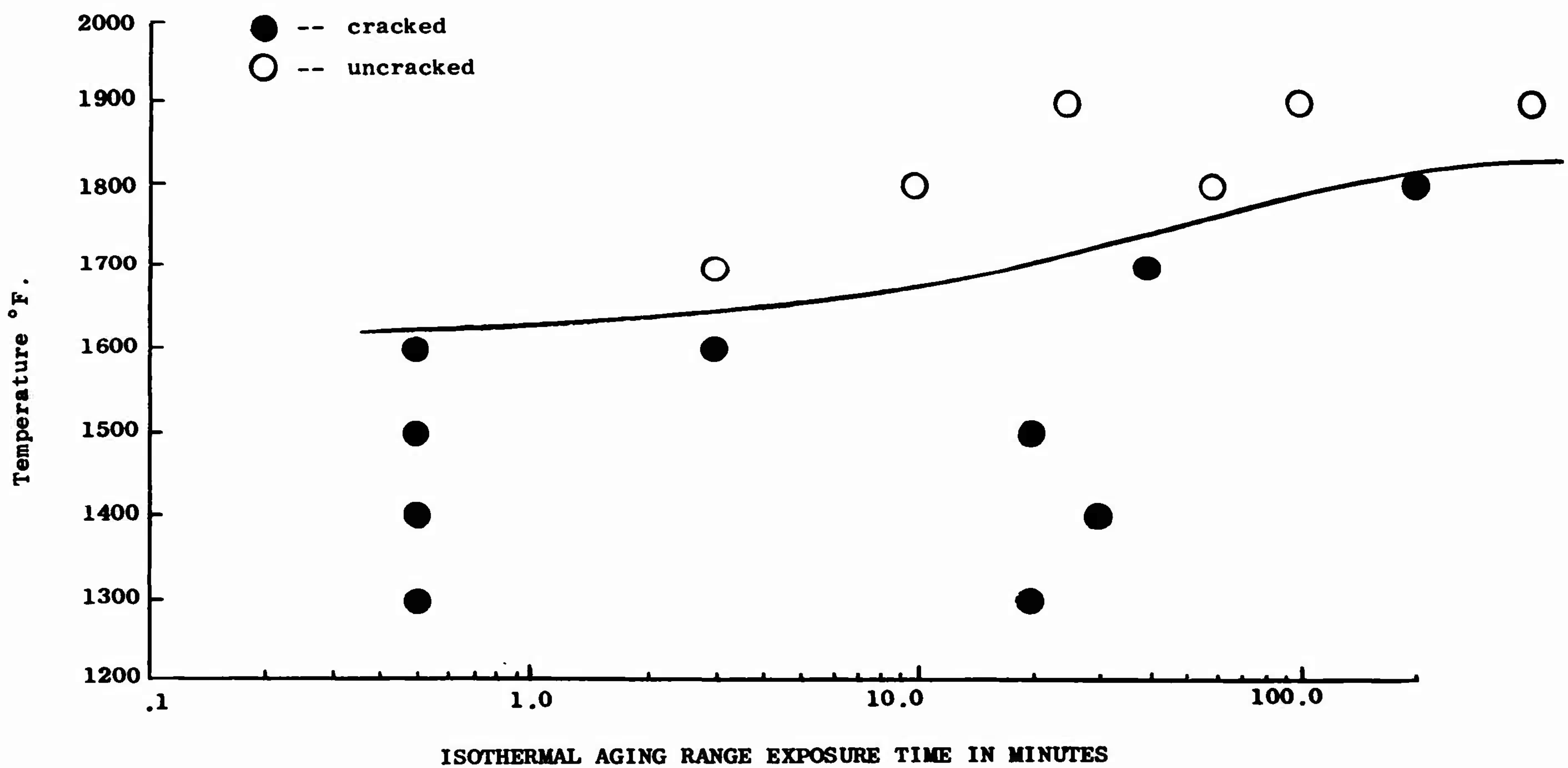


FIGURE 7. Crack Susceptibility C-Curve As Generated By The Patch Test Using The Type II Post Weld Heat Treating Procedure. Rene' 41 Heat T3-8556. Mill Annealed Prior To Welding.

Type III Crack Susceptibility C-Curves

The modifications of the post weld heat treating procedure which finally assured that strain-age cracking was occurring solely during the isothermal aging exposure are shown schematically in the bottom view of Figure 3.

The patch test assembly was inserted into a 1000°F furnace for 15 minutes; rapidly heated (2 minutes heating time) to a predetermined isothermal aging temperature and held for a specific length of time; rapidly heated to the solution temperature of 1975°F; held at 1975°F for one hour; furnace cooled (3-8°F/minute) to 1100°F and air cooled.

Heating the patch test assembly from the isothermal aging temperature to the 1975°F solution temperature and holding there prior to cooling eliminated the crack sensitive microstructure in the heat affected zone of the welds and fully stress relieved the weldment. Furnace cooling from the solution temperature further assured that no cracking would occur during cooling.

Typical Type III C-curves are shown in Figures 8 and 9 for heats T3-8565 and T4-8670, respectively.

The Type III C-curve satisfactorily identified cracking which would occur during continuous heating of a highly restrained Rene' 41 weldment to the solutioning temperature.

A further confirmation that the cracking which was developed in the Type III post weld heat treating cycle represented the cracking which

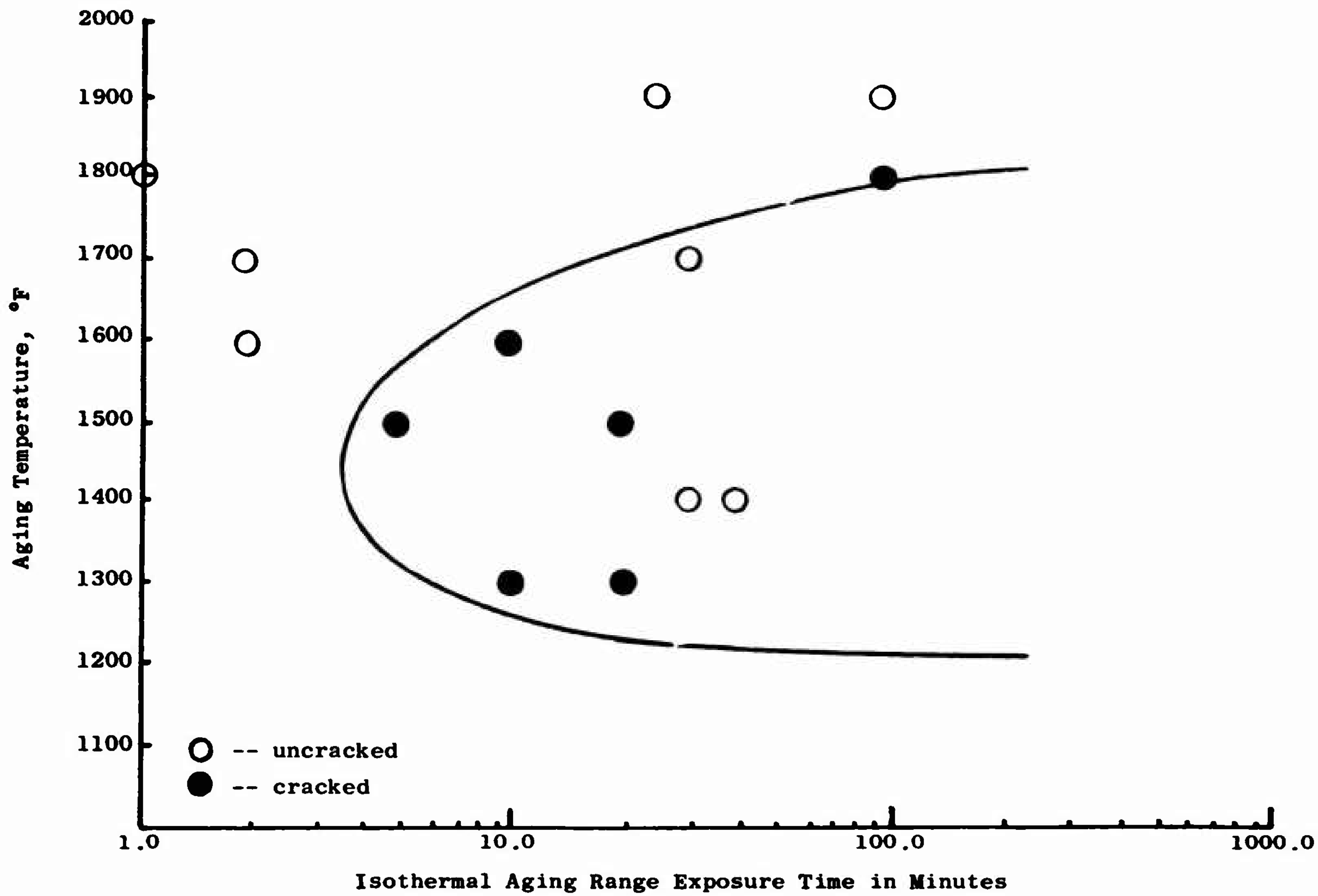


FIGURE 8. Crack Susceptibility C-Curve As Generated By The Patch Test Using The Type III Post Weld Heat Treating Procedure. Rene' 41 Heat T3-8565. Mill Annealed Prior To Welding.

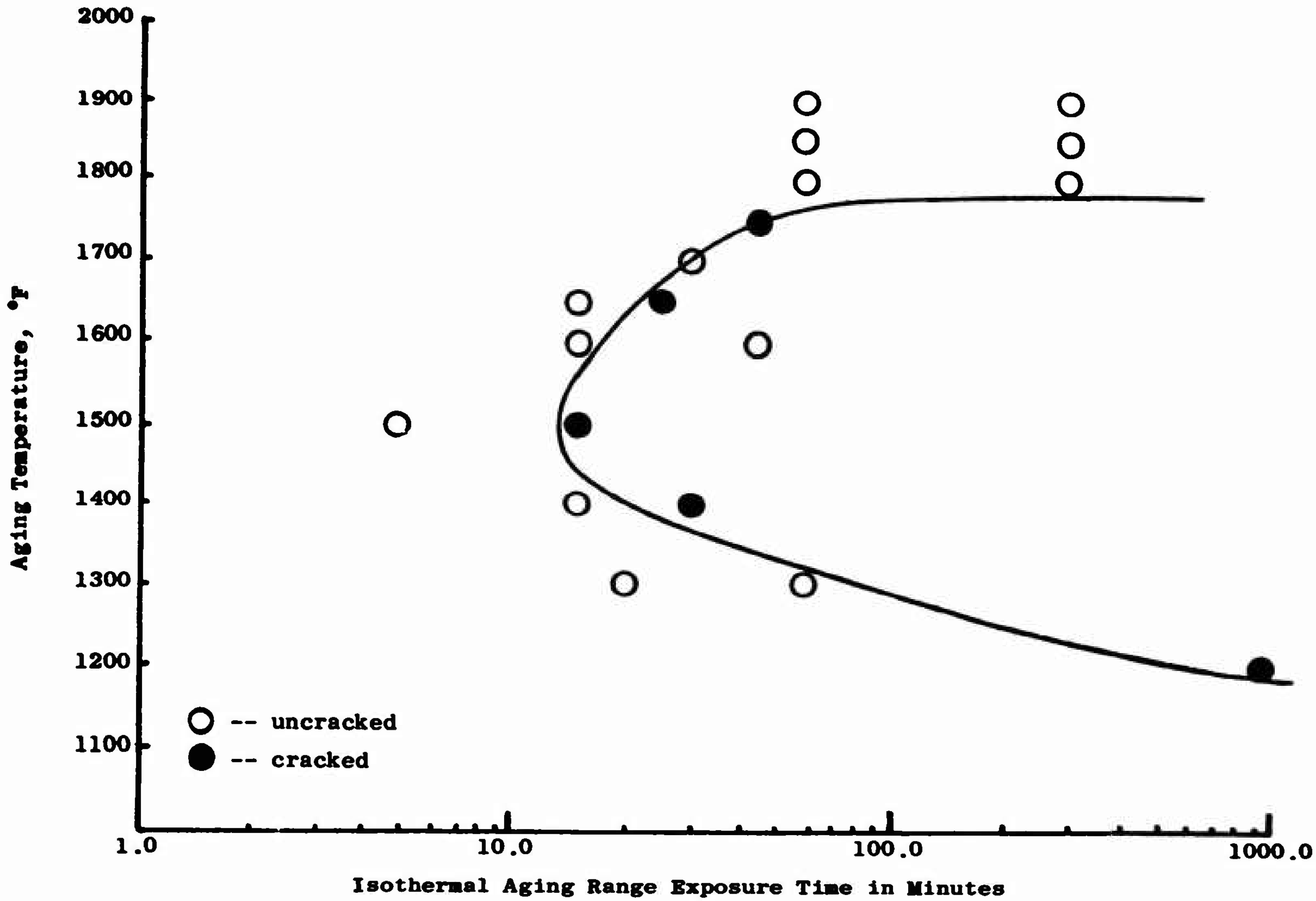


FIGURE 9. Crack Susceptibility C-Curve As Generated By The Patch Test Using The Type III Post Weld Heat Treating Procedure. Rene' 41 Heat T3-8670. Mill Annealed Prior To Welding.

would occur during continuous heating was provided by the following test. Several Rene' 41 patch test assemblies were heated to the solutioning temperature at various heating rates--some of which were selected to pass through the isothermally defined C-curve. Examination of the patch tests revealed that the patch tests whose heating curves intersected the C-curve were cracked. The others were not. These results are shown graphically in Figure 10 and further confirmed that the Type III C-curve accurately identified cracking which would occur during heating a restrained Rene' 41 weldment to the solutioning temperature.

Therefore, the Type III post weld heat treatment was selected for further studies of the effects of heat treatment, chemical composition, and other variables on the strain-age cracking resistance of Rene' 41.

1.5 Base Line Crack Susceptibility C-Curves

Two additional heats of Rene' 41 were evaluated for weldability using the Type III post weld heat treatment to serve as a base line of comparison for subsequent weldability studies. A crack resistant and crack sensitive heat of Rene' 41 were selected for this purpose.

The representative crack resistant heat was identified from last year's constant stress "Gleeble" results as Experimental Heat Number 10. A production heat of Rene' 41, Heat Number 11*, was found to be highly susceptible to cracking during the generation of its Type III C-curve and was selected, therefore, as the representative crack sensitive heat of Rene' 41. Figure 11 shows the catastrophic cracking exhibited by Heat Number 11 when isothermally aged at 1450°F for 30 minutes (all other processing per Type III

*This production heat of Rene' 41 (#11) is not to be confused with an Experimental Heat No. 11 which was evaluated in AFML-TR-66-324, Part I. Future reference in this report to Heat No. 11 will refer to Production Heat No. 11.

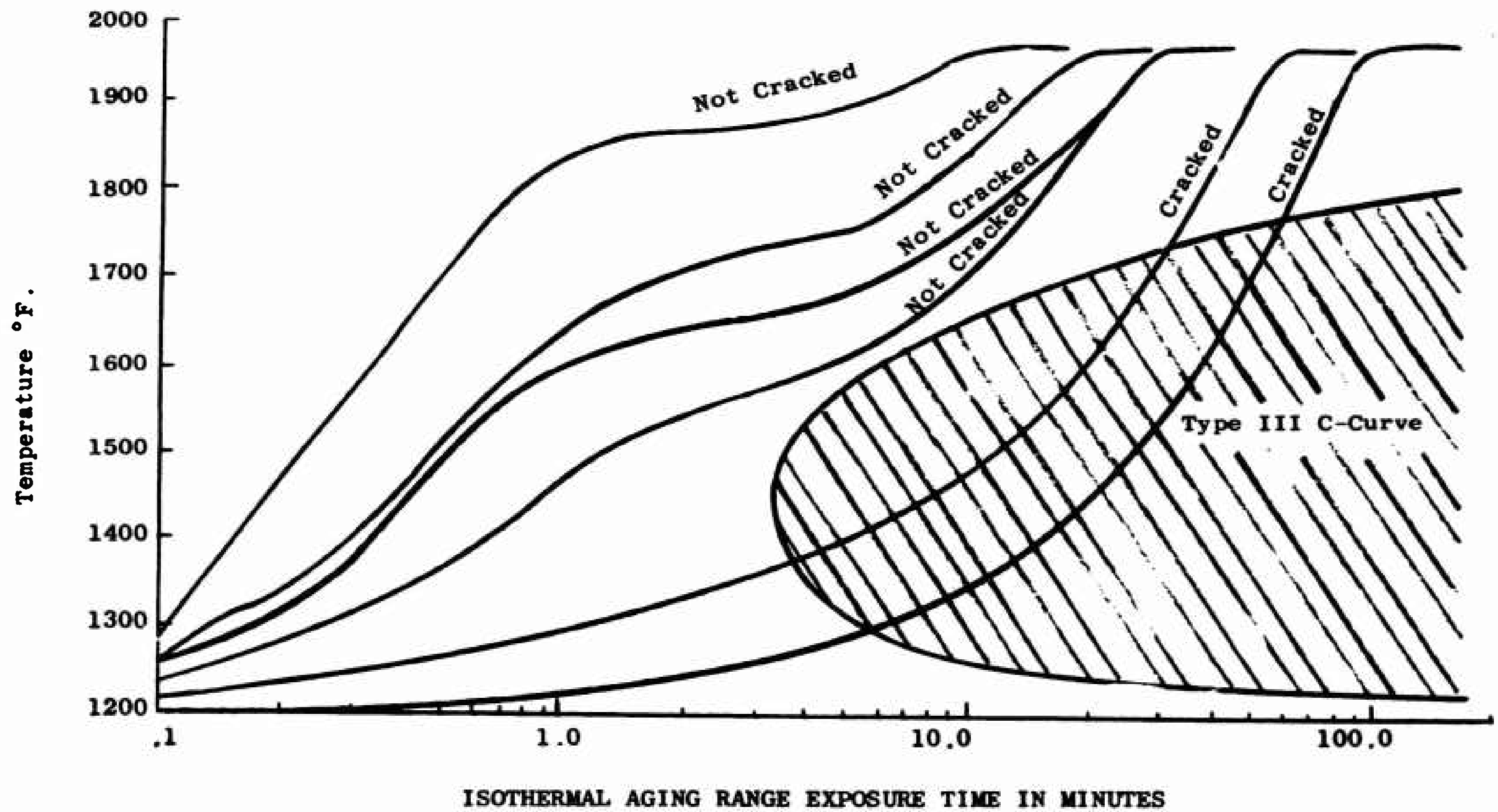


FIGURE 10. Crack Susceptibility C-Curve As Generated By The Patch Test With Superimposed Continuous Heating Curves. Rene' 41 Heat T3-856

FIGURE 11. Severe Cracking Occurring in a Patch Test Heat Number 11 Isothermally Aged at 1450°F for 30 Minutes Using Type III Post Weld Heat Treatment.

Mag: 1 X

C-curve procedure).

The Type III C-curve for the Experimental Heat Number 10 is shown in Figure 12 and for the production Heat Number 11 in Figure 13. Note that the critical nose of the crack resistant Experiment Heat Number 10 was further to the right than the nose for the crack sensitive heat. The C-curves are superimposed in Figure 14. Thus, the location of these two curves in the aging range of Rene' 41 constituted proof that the method used to generate the Type III C-curve yielded results which accurately detected differences in the strain-age cracking characteristics of a Rene' 41 weldment during heating to the solution temperature. As a consequence, these two curves were used as the standard to gauge the effect of processing, chemical composition, and metallurgical variables on the weldability of Rene' 41. Changes in these variables which moved the C-curve to the right increased resistance to strain-age cracking. Changes which shifted the C-curve to the left decreased resistance to strain-age cracking.

These two heats (Numbers 10 and 11) with widely different resistances to strain-age cracking also provided material with which the ability of the "Gleeble" test procedure to detect differences in strain-age crack resistance could be determined.

2.0 Modification of the "Gleeble" Test Procedure

2.1 Background

As previously mentioned, one of the major disadvantages of using the circular patch test as the tool for determining strain-age crack

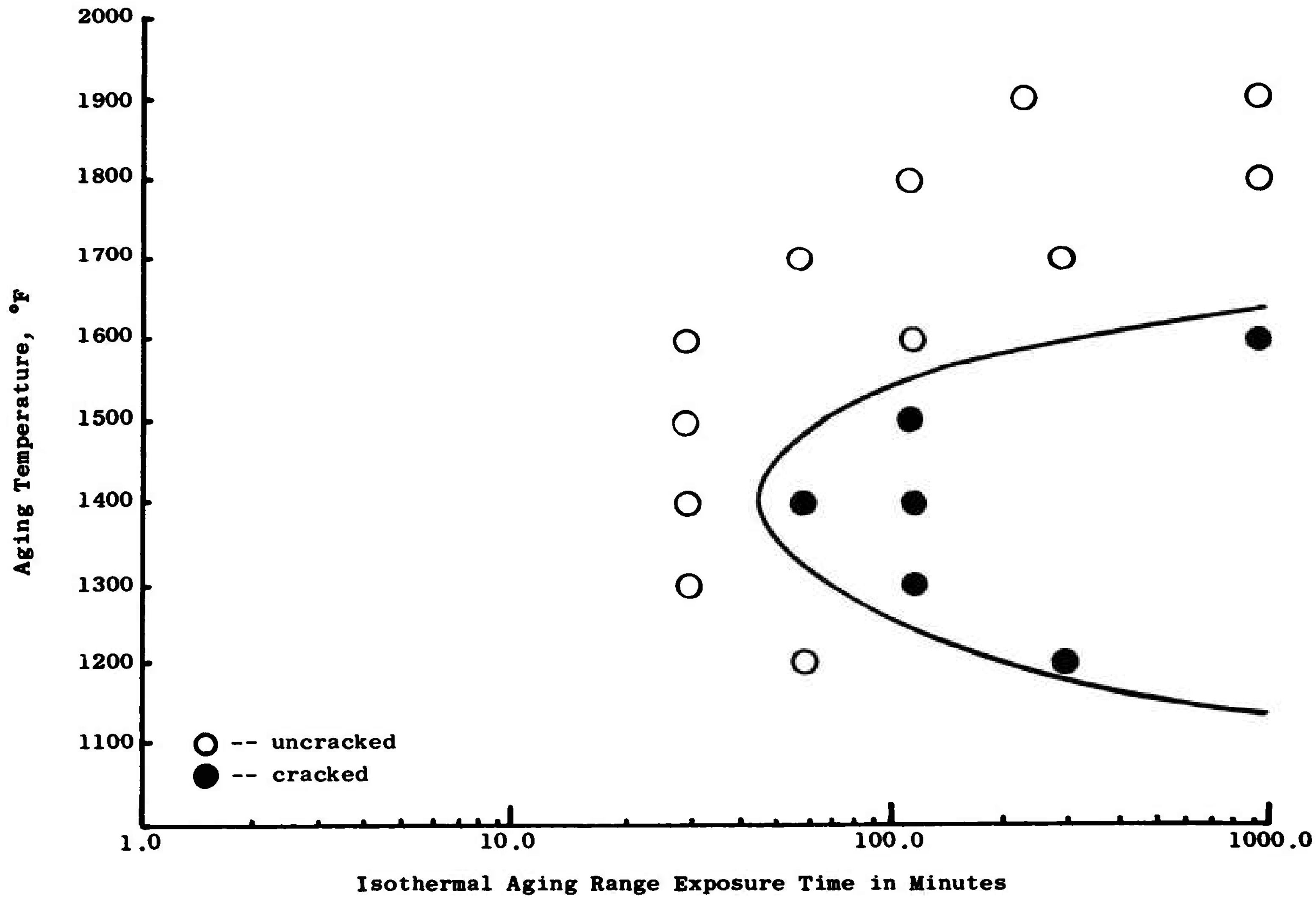


FIGURE 12. Crack Susceptibility C-Curve As Generated By The Patch Test Using The Type III Post Weld Heat Treating Procedure. Rene' 41 Heat Number 10. Mill Annealed Prior To Welding.

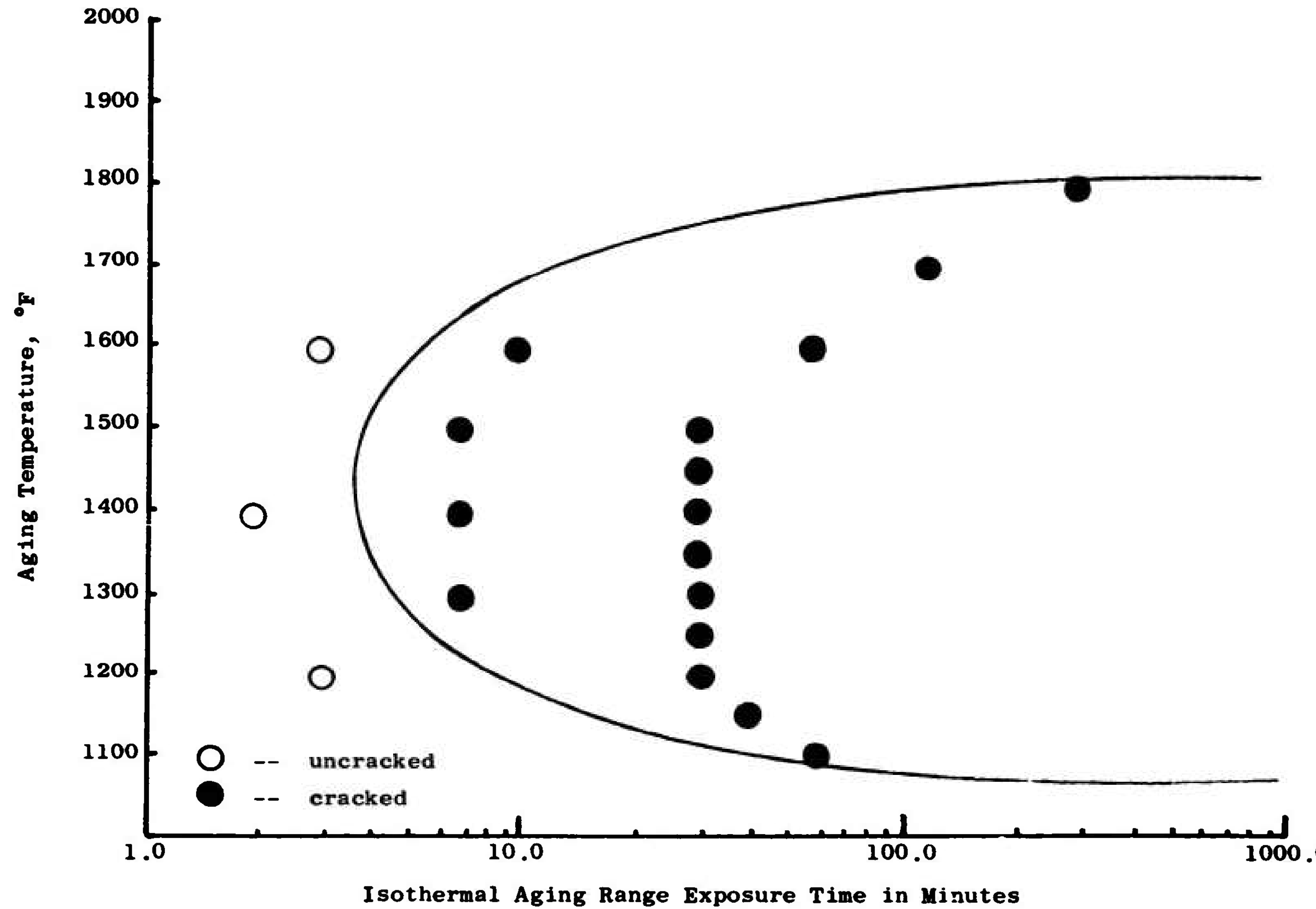


FIGURE 13. Crack Susceptibility C-Curve As Generated By The Patch Test Using The Type III Post Weld Heat Treating Procedure. Rene' 41 Heat Number 11. Mill Annealed Prior To Welding.

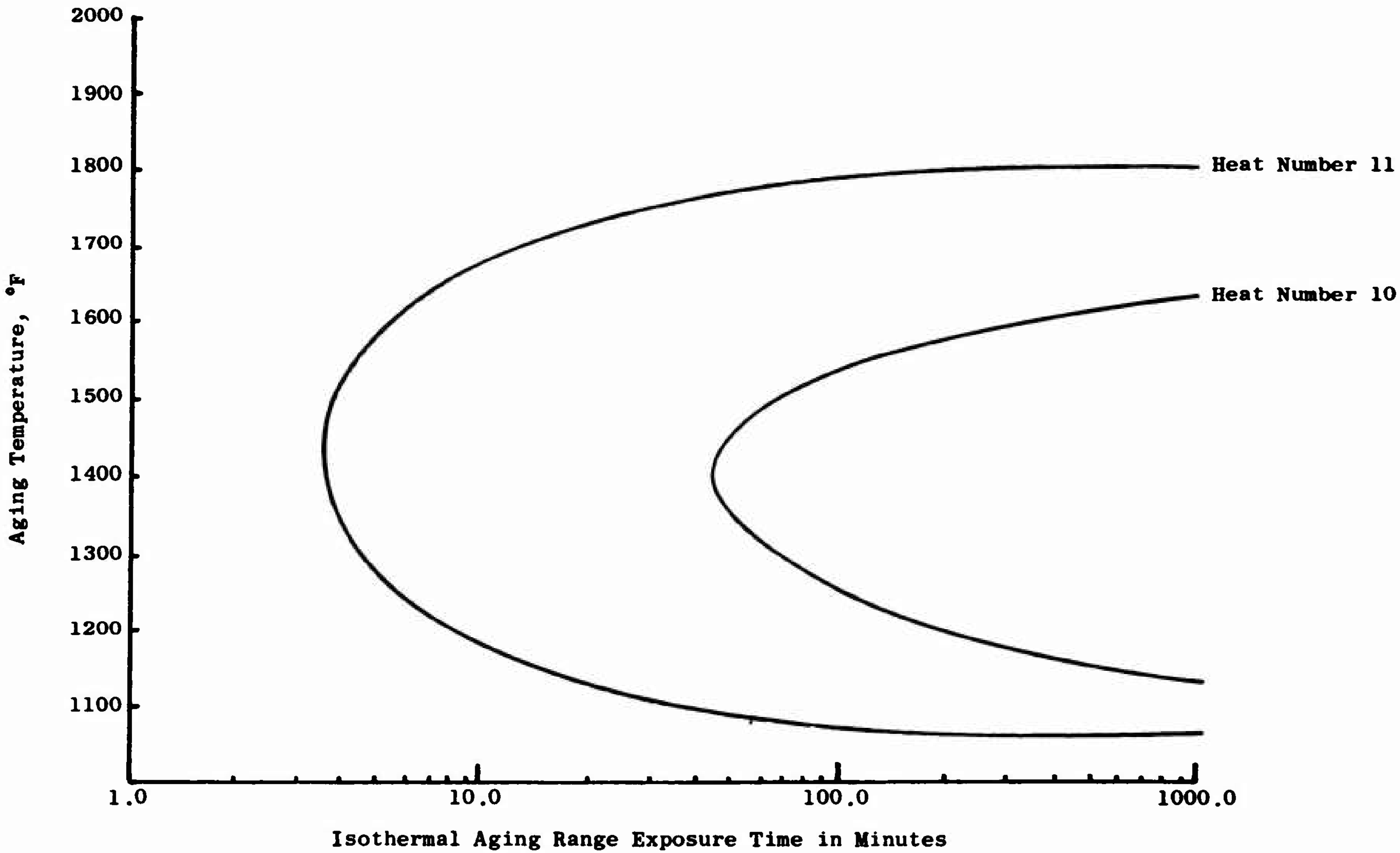


FIGURE 14. Crack Susceptibility C-Curves From Rene' 41 Heats Number 10 and 11. (Shown Separately in Figures 12 and 13.)

susceptibility was that the element of restraint or stress, for the most part, was unknown but reproducible. In fact, all that could be documented about the restraint or stress factor was that it was large enough to generate strain-age cracking as long as the other pertinent variables -- metallurgical conditions, temperature, and time -- had a specific set of values. Moreover, the circular patch test assembly was relatively expensive as a laboratory testing specimen and manufacturing and processing it through the appropriate welding and heat treatment procedures to obtain the desired results was comparatively time consuming. Thus, the need to obtain a more quantitative, cheaper, and faster testing procedure for investigating strain-age cracking phenomena was apparent.

The "Gleeble" equipment was used to develop a quantitative crack susceptibility testing procedure. Figure 15 shows the "Gleeble", a high precision time-temperature-stress or time-temperature-strain device. This equipment was capable of accurately programming, controlling and monitoring temperatures up to the melting point of any iron or nickel base alloy at heating rates ranging from 25°F/hour to 300°F/second and cooling rates ranging from 25°F/hour to 250°F/second at 1000°F. Strain rates at any temperature can be varied from 0.10 in/in/second to 20.0 in/in/second over an effective gage length of 0.2 inch in a 0.7 inch heating space. The temperature distribution across the welded "Gleeble" test specimen was determined and is shown on the next page. The temperature was considered essentially constant over the region of the weldment.

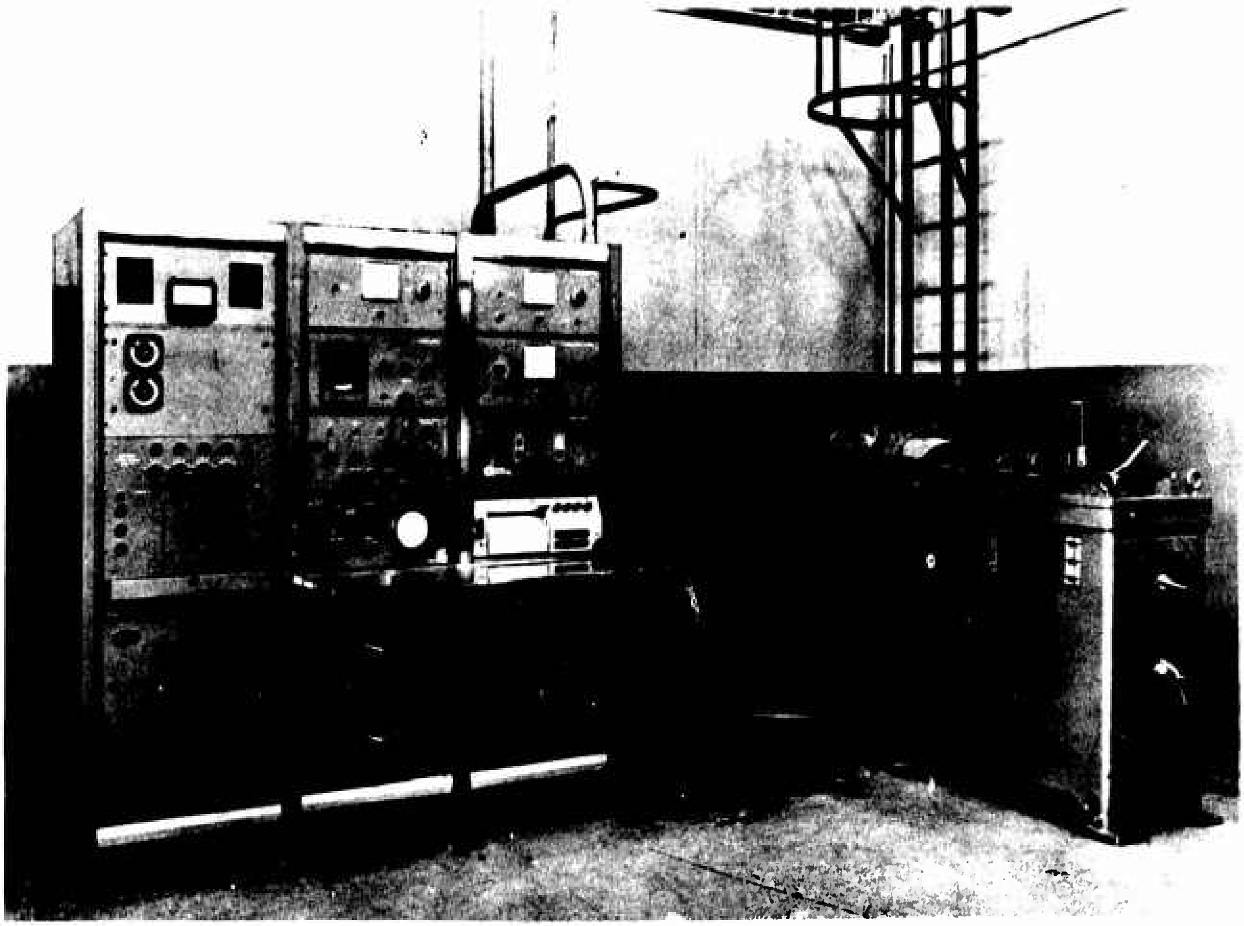


FIGURE 15. Gleeble Apparatus

Distance From Center of Specimen	-.385"	-.185"	-.065"	+.065"	+.400"
	900°F	885°F	905°F	890°F	865°F
	1355°F	1390°F	1400°F	1365°F	1355°F
	1535°F	1580°F	1600°F	1580°F	1535°F
	1770°F	1780°F	1780°F	1775°F	1770°F

Any amount of load, up to the breaking strength of the material can be applied to a specimen for any predetermined time and temperature during the testing cycle. Unless otherwise noted, the actual testing of specimens was performed in an atmosphere chamber partially purged with argon.

The "Gleeble" is capable of applying a uniaxial load. It was recognized that to duplicate the stress state operating during the processing of a patch test (or actual welded fabrication), the finally selected "Gleeble" specimen configuration must be such that a biaxial stress is applied to the heat affected zone when a uniaxial load is applied to the specimen.

During the first year's effort, several specimen configurations were evaluated[(1)]. The "Gleeble" specimens were manually gas tungsten arc welded. A small fixture with a ground copper strip and argon gas backing was used. Parameters were as follows:

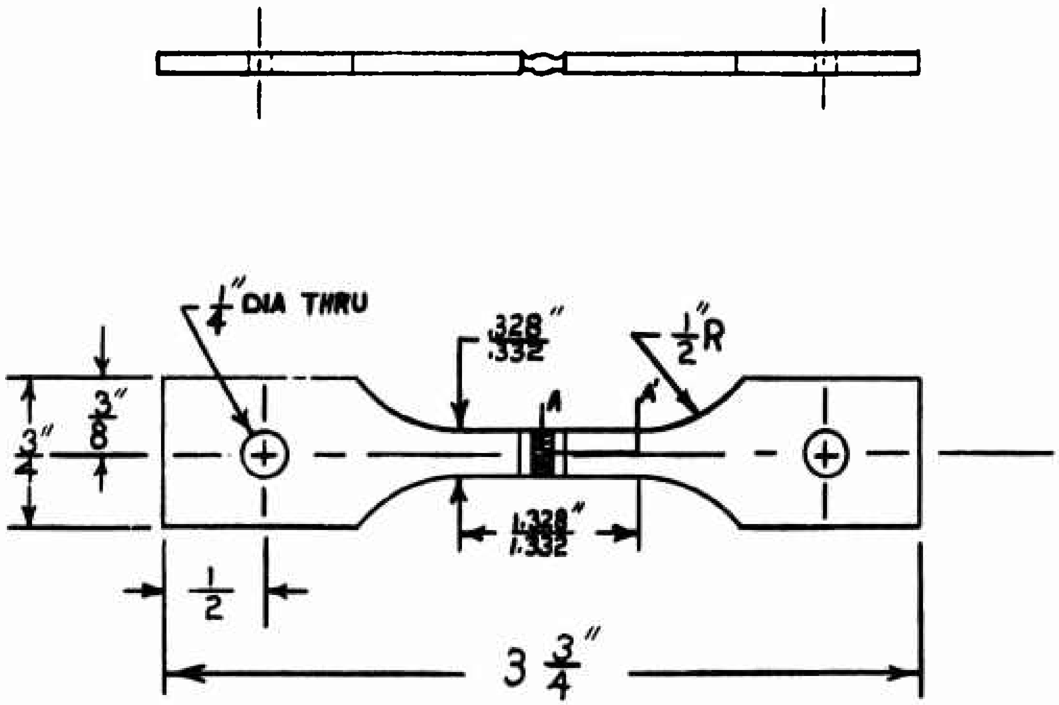
Current - 65 amps for 0.060 inch joints
- 40-45 amps for 0.030" joints

Voltage - 8-10 volts

Welding speed - 5 ipm

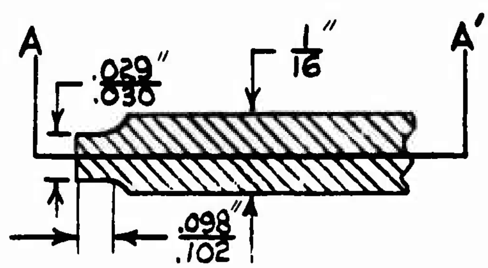
Filler - Hastelloy W

The specimen finally selected is shown in Figure 16. The testing procedure which was developed was essentially a stress rupture test (i.e., constant load) across an as-welded joint with a biaxiality stress state imposed on the heat affected zone. This test procedure was capable of detecting different



Cross Section A - A'

Scale 4:1



Preparation Before Welding

FIGURE 16. Reduced Face Welded "Gleeble" Specimen.

levels of strain-age crack susceptibility between heats of Rene' 41.

The constant load "Gleeble" testing procedure is schematically illustrated in Figure 17 and was conducted as follows:

1) The "Gleeble" specimen was loaded at room temperature to a stress value that was a certain percentage of the tensile strength at the intended isothermal aging temperature.

2) Maintaining constant load, the temperature of the specimen was increased at the rate of 1200°F/minute to 1000°F, held there for 15 minutes, then raised to preselected aging temperature at the same rate and held there isothermally until fracture occurred.

3) Holding the load constant, the specimen was allowed to strain freely until fracture occurred.

4) The fracture strength of one heat of material was determined to serve as a base line of comparison.

The strengths determined in 1-3 above were plotted versus the Larson-Miller time-temperature parameter. The resultant curve was then used to determine failure times of "Gleeble" specimens versus aging temperatures at a selected stress level. This stress level was a constant percentage of the reference strength.

The two heats of Rene' 41 (Heats Number 10 and 11) which were identified with the patch test as having widely different resistances to strain-age cracking (Figure 14) were subjected to weldability evaluation using the constant load "Gleeble" test procedure. The results are given in

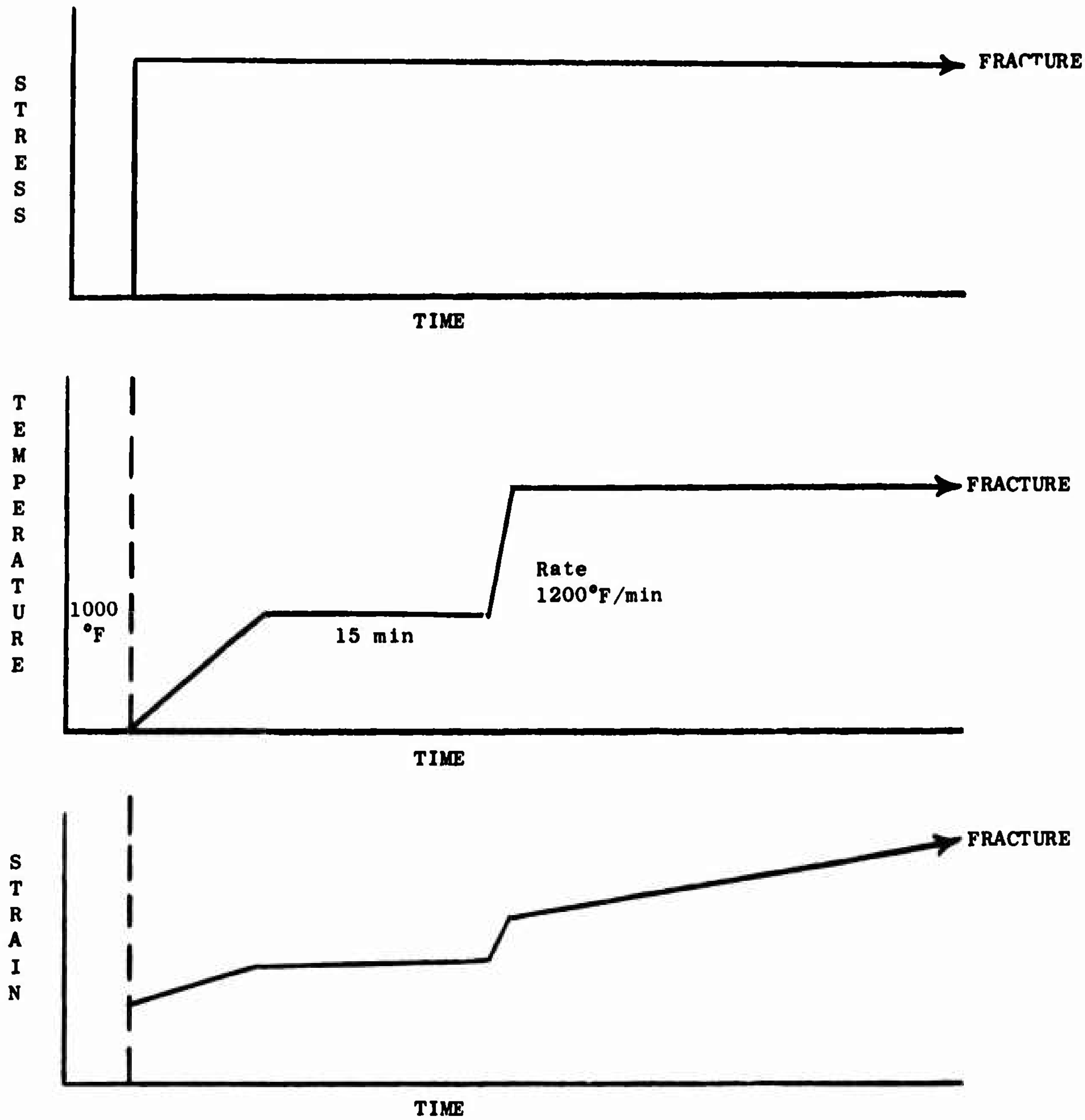


FIGURE 17. Constant Stress Gleeble Testing Procedure.

Tables 1 and 2 and shown graphically in Figure 18. Comparison of Figure 18 with Figure 14 shows that both testing procedures detect the superior weldability of Heat Number 10. Thus, the constant load "Gleeble" test procedure was capable of detecting differences in weldability much the same as the restrained patch test procedure.

A typical example of heat affected zone cracking is a specimen tested in the "Gleeble" shown in Figure 19. The cracking occurred immediately adjacent to the weld fusion line which is typical for strain-age cracks.

The greatest departure of this test procedure from representing an actual weldment during post weld heat treatment was the constant load procedure for applying stress. A restrained weldment is more nearly a constant strain test with stress relaxation occurring during heat treatment. This consideration led to the development of a constant strain "Gleeble" testing procedure which would more accurately duplicate the stress state in a restrained weldment during post weld heat treatment.

2.2 Development of the Constant Strain "Gleeble" Test Procedure

Further development of a "Gleeble" testing procedure progressed along two interrelated routes: (1) the development of an appropriate test specimen design, and (2) the development of an appropriate testing procedure (primarily temperature and strain application cycles).

"Gleeble" Test Specimen Design

All "Gleeble" test specimens were made with a welded joint rather than a simulated heat affected zone at the center of the gage section.

TABLE 1

CONSTANT LOAD "GLEEBLE" TEST RESULTS FOR TIG WELDED

RENE' 41 EXPERIMENTAL HEAT NUMBER 10

Isothermal Aging Temperature °F	Reference Stress Level (ksi)	Percentage of Reference Stress (%)	Applied Stress (ksi)	Time To Failure (min)	Time-Temperature Parameter $T(20 + \log t) \times 10^{-3}$*
1300	102.0	82.9	84.5	180.0+	36.0
1400	106.0	78.0	82.7	59.0	37.2
1500	92.3	84.2	77.7	41.0	38.9
1600	77.0	82.5	63.5	33.0	40.7
1700	60.0	83.1	49.8	5.0	40.8
1800	40.3	75.3	30.4	15.0	43.8
1900	20.6	89.4	13.4	40.0	46.8
1400	106.0	59.4	63.0	180.0+	38.1
1500	92.3	57.0	52.6	180.0+	40.2
1600	77.0	56.2	43.3	180.0+	42.2
1700	60.0	50.4	30.2	29.0	42.5
1800	40.3	63.0	25.4	45.0	44.9
1900	20.6	64.1	13.2	156.0	48.2

*Time-temperature parameter = $P = T(C + \log t) \times 10^{-3}$

where: T = test temperature, degrees Rankin,
t = time to failure in hours,
c = a constant determined for each alloy, 20 for Rene' 41.

Specimen design: See Figure 16.

TABLE 2

CONSTANT LOAD "GLEEBLE" TEST RESULTS FOR TIG WELDED

RENE' 41 HEAT NUMBER 11

Isothermal Aging Temperature	Reference Stress Level (Kpsi)	Percentage of Reference Stress (%)	Applied Stress (Kpsi)	Time To Failure (min)	Time-Temperature Parameter $T(20 + \log t) \times 10^{-3}$
1310	102.0	40	40.9	137.0	35.8
1410	106.0	40	42.5	27.2	36.8
1525	92.3	40	37.0	3.1	37.2
1605	77.0	40	30.8	0.6	37.2
1700	60.0	40	24.0	14.2	43.3
1800	40.3	40	16.1	40.9	44.8
1910	20.6	40	8.3	14.3	45.9
1320	102.0	50	51.0	10.5	34.3
1410	106.0	50	53.0	3.2	35.0
1525	92.3	50	46.1	13.3	38.4
1620	77.0	50	38.5	0.3	36.8
1700	60.0	50	30.0	14.2	41.8
1825	40.3	50	20.1	6.0	43.4
1910	20.6	50	10.3	13.3	45.8
1310	102.0	60	61.2	8.0	33.8
1425	106.0	60	63.6	1.1	34.2
1520	92.3	60	55.4	1.0	36.0
1620	77.0	60	46.2	0.7	37.6
1700	60.0	60	36.0	0.65	38.9
1840	40.3	60	24.2	1.5	42.3
1915	20.6	60	12.4	3.3	44.5
1320	102.0	70	71.4	3.0	33.3
1400	106.0	70	74.2	0.8	33.6
1520	92.3	70	64.6	0.4	35.2
1600	77.0	70	53.8	0.3	36.6
1700	60.0	70	--	--	--
1820	40.3	70	28.2	1.7	42.1
1925	20.6	70	14.4	5.0	45.1

Specimen Design: See Figure 16.

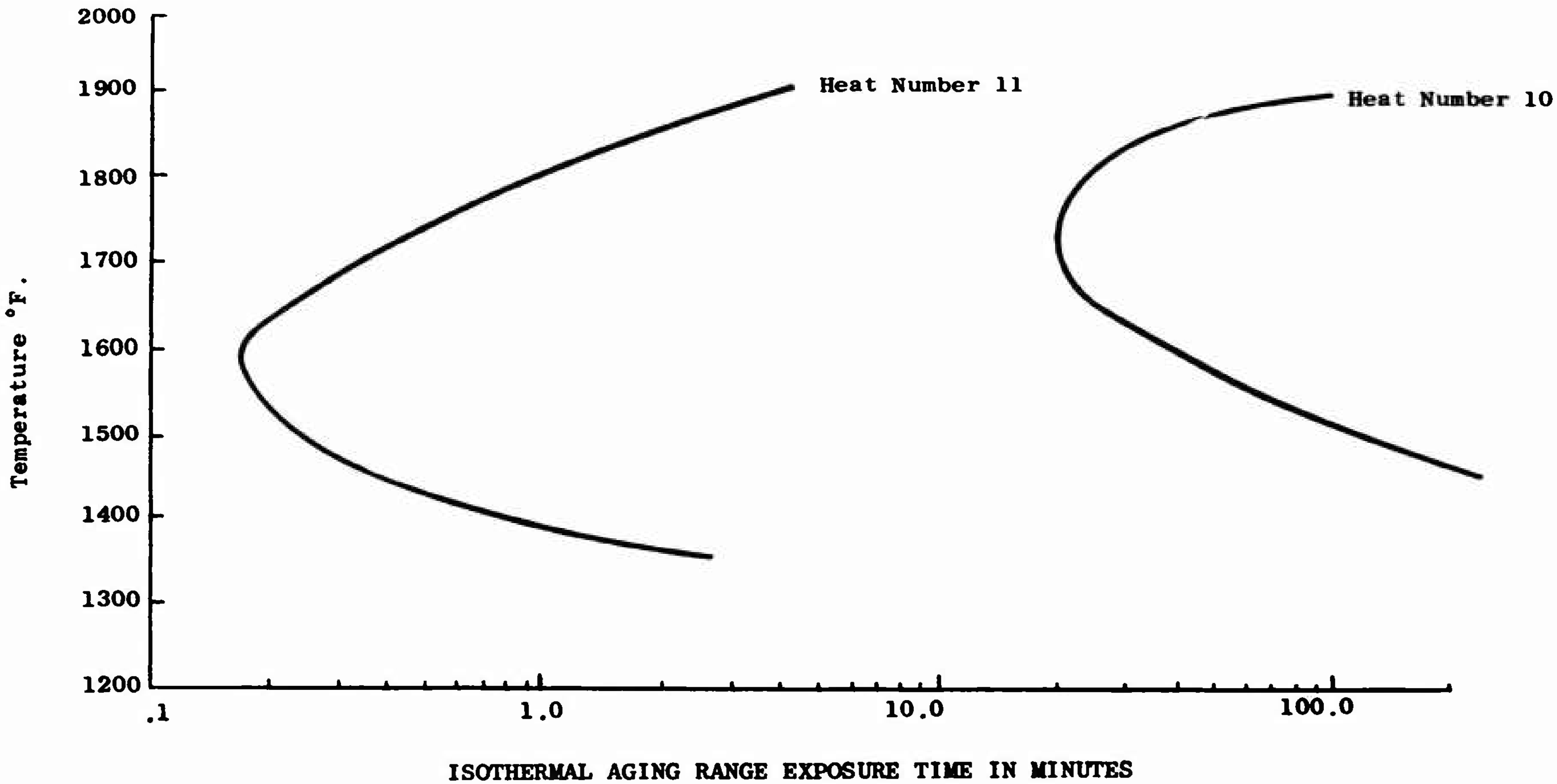


FIGURE 18. Crack Susceptibility C-Curves As Generated by the Gleeble Using the Constant Load Testing Procedure. The Curve for the 70% Reference Stress Level is Shown. Rene' 41 Heats Number 10 and 11 in the Mill Annealed Condition.

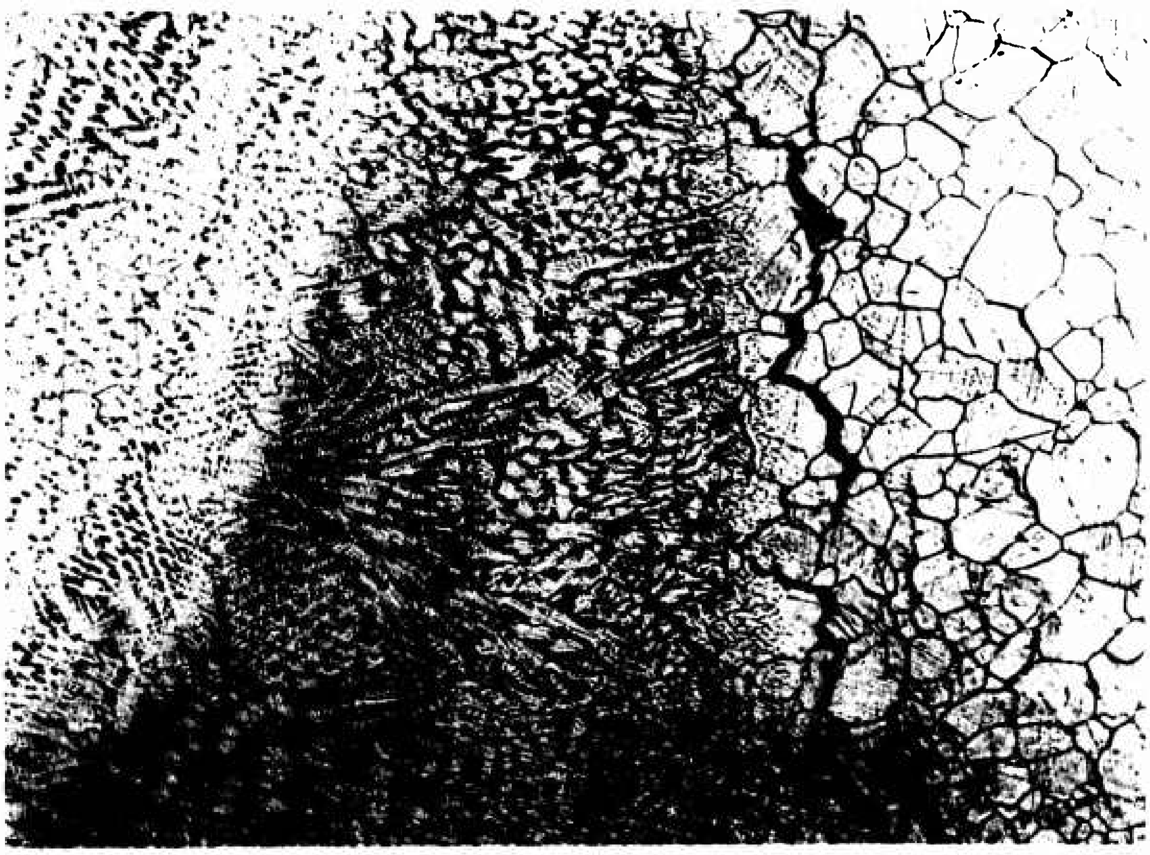


FIGURE 19. Rene' 41 Microstructure of Tested Gleeble Specimen Showing Typical Strain-Age Cracking. Experimental Heat Number 2 Tested 92 minutes at 1500°F.

Neg. No. M7859 and F7427 Mag: 100 X

The selection of the "Gleeble" test specimen design was based on two criteria: (1) the weld heat affected zone must be biaxially stressed, and (2) fracture must occur in the heat affected zone. These two conditions are known to exist when strain-age cracking occurs in a welded component.

The specimen designs considered are shown in Figures 16, 20, and 21. The differences in the specimens are primarily to change the biaxiality in the heat affected zone during uniaxial loading.

From a stress analysis of the patch test, it was estimated[2] that the biaxiality ratio (major stress/minor stress) in the patch test weld heat affected zone was 0.9. The welded specimen previously evaluated (shown in Figure 16) was estimated to have a ratio of 0.3 to 0.4. The ratio could further be increased to 0.8 to 0.9 by placing the weld at 45° to the tensile axis in a standard thickness specimen (Figure 20). A ratio of 0.9 to 1.0 can be developed by using a face reduced specimen with a weld at 45° to the tensile axis (Figure 21).

The specimen designs were evaluated along with the development of the testing procedure. It was found that very similar results could be obtained with each of the specimens. It was very difficult to machine the 0.030 inch lip on the welded edge of the 0.060 inch sheet and maintain a uniform lip thickness on the same panel and between different panels.

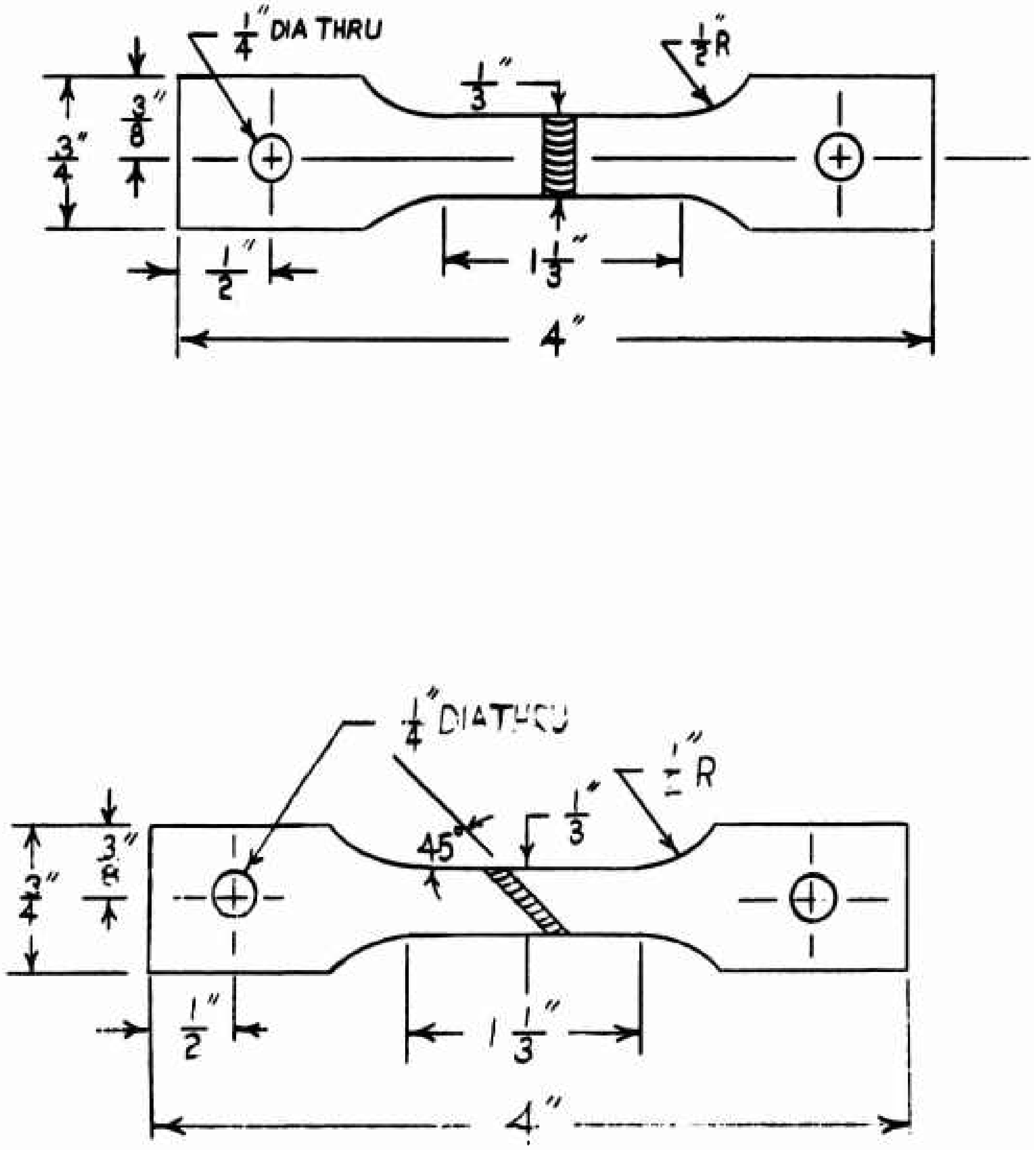
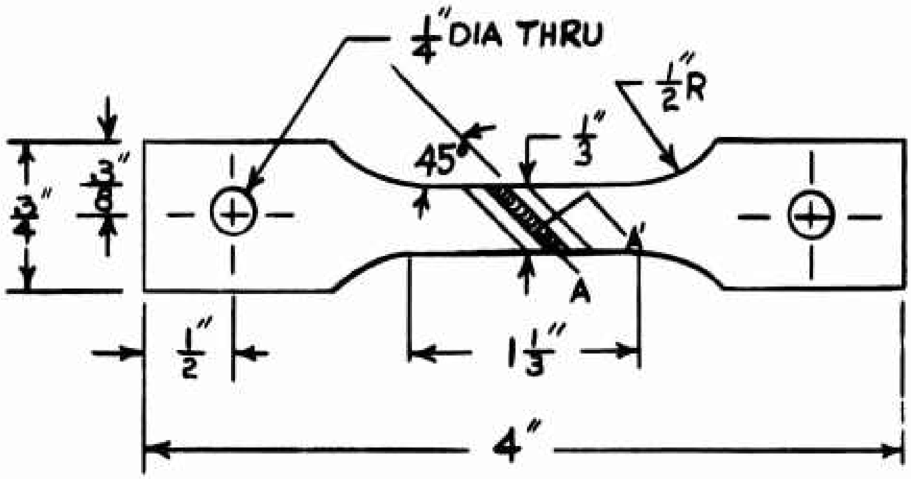


FIGURE 20. Welded Test Specimens Used in the "Gleeble".



Cross Section A - A'

Scale 4:1

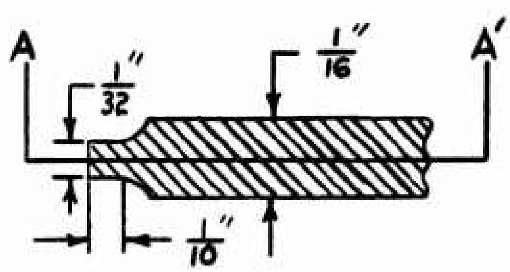


FIGURE 21. "Gleeble" Specimen With Reduced Face and the Weld at 45° to the Tensile Axis.

It was also preferable to maintain a high biaxiality ratio in the "Gleeble" specimen to closely duplicate the stress state in a restrained weldment. These considerations led to the selection of the specimen with a weld at 45° to the tensile axis, shown in Figure 20.

"Gleeble" Testing Procedure Development

The development of an appropriate constant strain procedure entailed the consideration of the following factors:

1) The effect of thermal expansion as the specimen is heated from room temperature to the isothermal aging temperature.
2) The sequence and method of applying the constant strain and maintaining it throughout the isothermal aging exposure.
3) The magnitude of the constant strain value for any isothermal aging temperature and its corresponding effect on the magnitude of the peak initial stress value and the relationship that both of these factors have on the time and location of cracking.
4) The detection of the time for cracks to initiate during isothermal aging under constant strain loading.

Thermal expansion of the specimen was accounted for by applying the strain on the specimen after the specimen had reached the isothermal aging temperature.

Immediately applying the full predetermined strain value after the specimen reached the isothermal aging temperature resulted in high peak stress values that often exceeded the capacity of the load cell and caused the specimen to rupture prematurely. It was noted that this rapid strain application did not represent the stress-strain conditions of a restrained weldment during heat treatment. The stress-strain relationship during post weld heat treatment of a restrained weldment can best be visualized by consideration of the restrained circular patch test. When a patch test assembly is isothermally aged, the temperature of the base plate assembly lagged the temperature of the center patch area during heat-up. The difference in thermal expansion between the thick and thin sections would relax the residual stresses. As the heavy base plate increased in temperature, it expanded and gradually restored the orginal strain on the center patch area. The average time to temperature equalization between the center patch area and the heavy base plate varied slightly with the isothermal aging temperature as follows:

Isothermal Aging Temperature (°F)	Average Time to Temperature Equalization Between the Center Patch and Base Plate. (minutes)
1200	14.0
1300	14.5
1400	16.0
1500	16.5
1600	15.0
1700	13.0
1800	11.5

This condition was duplicated in the constant strain "Gleeble" test procedure by elongating the "Gleeble" test specimen in small discrete increments until the maximum strain value was reached. The time to apply the elongation to the "Gleeble" specimen corresponded to the times in the above table.

The predetermined constant strain value on the "Gleeble" specimen was set and maintained by a variable strain device consisting of a differential screw and a micrometer collar. This device was calibrated in 0.001 inch increments and had a range that varied from 0.001 inch to one inch.

The constant strain "Gleeble" test procedure is schematically illustrated in Figure 22 and described below:

1) The "Gleeble" specimen was placed into the machine without applying load or elongation and heated at 1200°F; heated to a specified aging temperature and held there isothermally until complete fracture occurred or until 45 minutes had expired.

2) Strain was applied to the specimen after it reached the isothermal aging temperature; the strain was applied incrementally according to the schedule listed above, the strain was held constant at the predetermined value until complete fracture occurred or until 45 minutes had expired.

3) The stress level increased in segments as the incremental strain increased and peaked at the constant strain value. The stress gradually decreased (stress relaxation) until the specimen fractured, or 45 minutes had expired.

A catastrophic failure was recorded by the "Gleeble" when the stress, strain, and temperature indicators returned abruptly back to their respective reference levels. If the failure was gradual, it could only be observed by the unaided eye giving rise to indeterminacy in time values.

All specimens were tested by the same operator. The effect of temperature on crack observation was as follows:

1) At the lower temperatures in the aging range (1200°F, 1300°F), the specimen was a relatively dark red and the contrast of the cracked edge to the rest of the specimen was not very great.

2) At the intermediate temperatures (1400°F, 1500°F, 1600°F), the cracked edge stood out in greater relief to the rest of the specimen making it easier to detect.

3) At the higher temperatures (1700°F, 1800°F), the heated area was a much brighter red to orange and the crack did not contrast very much with its surroundings.

Thus, at the intermediate temperatures, it was easier to detect smaller cracks than at the lower and higher temperatures.

If a specimen ran for 45 minutes without cracking, the test was discontinued. Forty-five minutes was considered as "runout", that is, the practical limits of time that could be devoted to the testing of one specimen.

With the finalization of the constant strain procedure it became necessary to establish correlation between results obtained with the constant strain "Gleeble" test procedure and patch test. It was also necessary to establish a base line against which the effects of metallurgical and processing variables on the strain-age crack susceptibility of Rene' 41 could be determined.

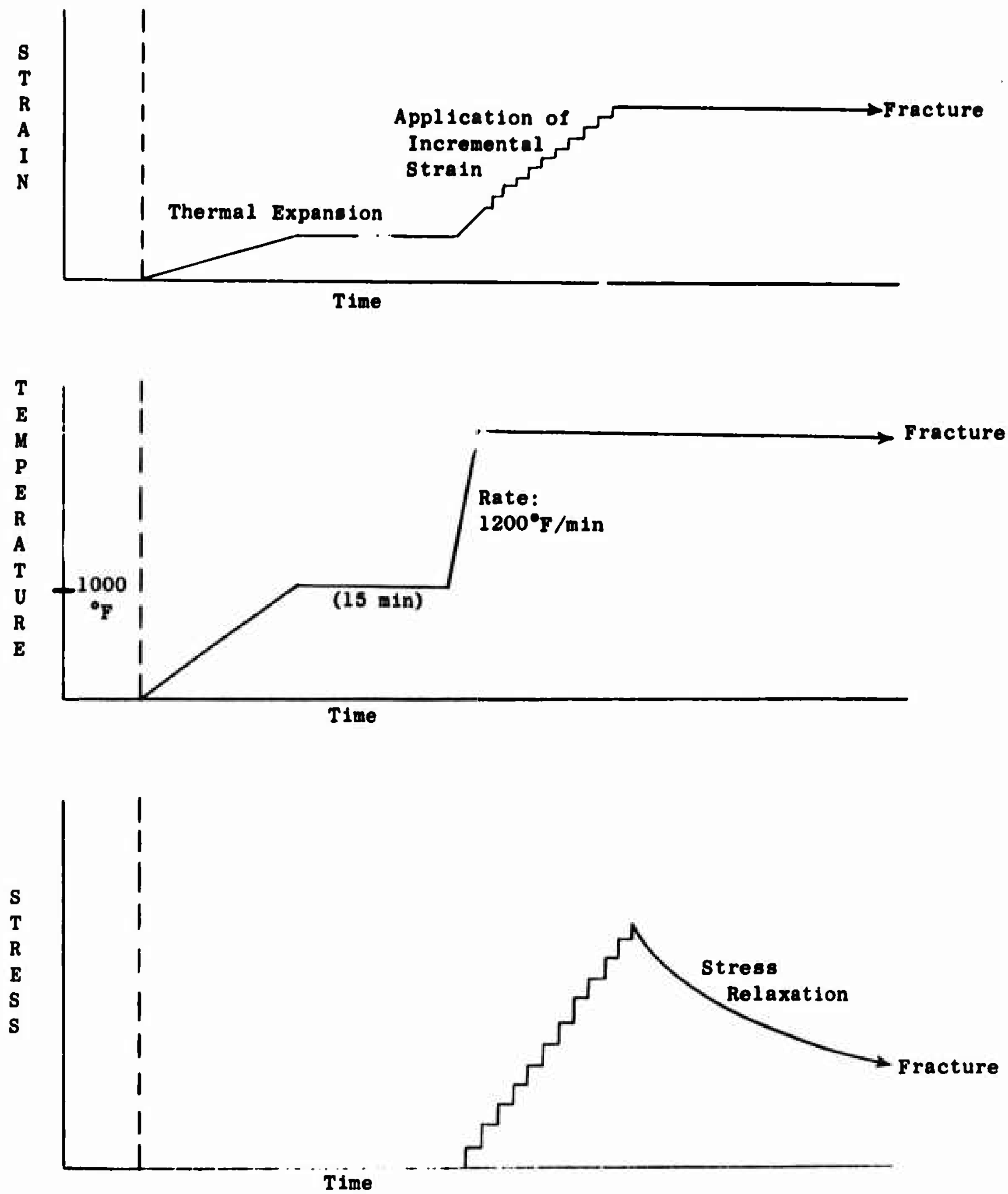


FIGURE 22. Constant Strain "Gleeble" Test Procedure

Correlation Between Constant Strain "Gleeble" Test Results and Patch Test Results

The crack sensitive heat, Heat Number 11, was used to determine the range of specimen elongation that would produce strain-age cracking. It was found that, for all the isothermal aging temperatures tested, a minimum constant elongation of 0.020 inch and a maximum constant elongation of 0.045 inch yielded the most satisfactory results. Below 0.020 inch, no strain-age cracking occurred; above about 0.045 inch, the specimen failed prior to reaching the intended strain value. Within this range, it was found that an elongation of 0.035 inch could be used satisfactorily for testing at each of the aging temperatures.

To establish a correlation between the results of crack susceptibility as determined by patch testing and the "Gleeble", Heat Number 11 and the Experimental Heat Number 10 were tested in the "Gleeble" using the constant strain technique with an elongation value of 0.035 inch at all aging range temperatures tested. These results are presented in Table 3 and Figure 23 where the actual specimens with their associated fractures are shown. The failure times are shown graphically in Figure 24.

All of the specimens of the Experimental Heat Number 10 ran the entire 45 minutes without any visual cracking occurring. A very fine, tight cracking was detected by fluorescent penetrant inspection in the specimens tested at 1600°F and 1800°F. Specimens of Heat Number 11, the crack sensitive heat, exhibited severe cracking prior to the 45 minutes duration at all temperatures except the extremities, 1200°F and 1800°F. The times of failure

TABLE 3

RESULTS OF CONSTANT STRAIN GLEEBLE TESTING THE CRACK SENSITIVE AND CRACK RESISTANT HEATS OF RENE' 41

Crack Sensitive Heat - Heat Number 11
Crack Resistant Heat - Experimental Heat Number 10
Constant Elongation Value - 0.035"
Specimen Type - 45°, TIG welded

Temp. °F	Exposure Time at Temperature after full Adaption of Constant Strain (Minutes)		Initial Stress (ksi)		Final Stress (ksi)		Location of Fracture	
	Heat #11	Heat #10	Heat #11	Heat #10	Heat #11	Heat #10	Heat #11	Heat #10
1200	45.0	45.0	63.2	57.2	61.1	54.6	None	None
1300	33.5	45.0	55.3	57.9	51.0	55.5	Transverse (1)	None
1400	5.0	45.0	67.1	53.9	58.8	48.4	HAZ	None
1500	1.5	45.0	66.2	58.8	44.7	45.6	HAZ	None
1600	1.6	45.0	53.9	59.2	50.7	32.3		HAZ (2)
1700	20.0	45.0	39.1	39.4	5.6	15.7	HAZ (3)	None
1800	45.0	45.0	23.1	26.5	7.45	7.3	HAZ (2)	HAZ (2)

Legend:

(1) This fracture was transverse to the axis of the specimen propagating through the parent metal, heat affected zone and weld. There appeared to be no preferential propagation along the heat affected zone.

(2) These failures were small heat affected zone cracks which were detected by a flourescent penetrant inspection after the 45 minute time limit.

(3) Initial cracking was observed to occur after 1.6 minutes after the full application of constant strain. Complete fracture did not occur until after 20 minutes.

Temperature °F	Crack Sensitive Heat	Crack Resistant Heat

1200

1300

1400

1500

1600

1700

1800

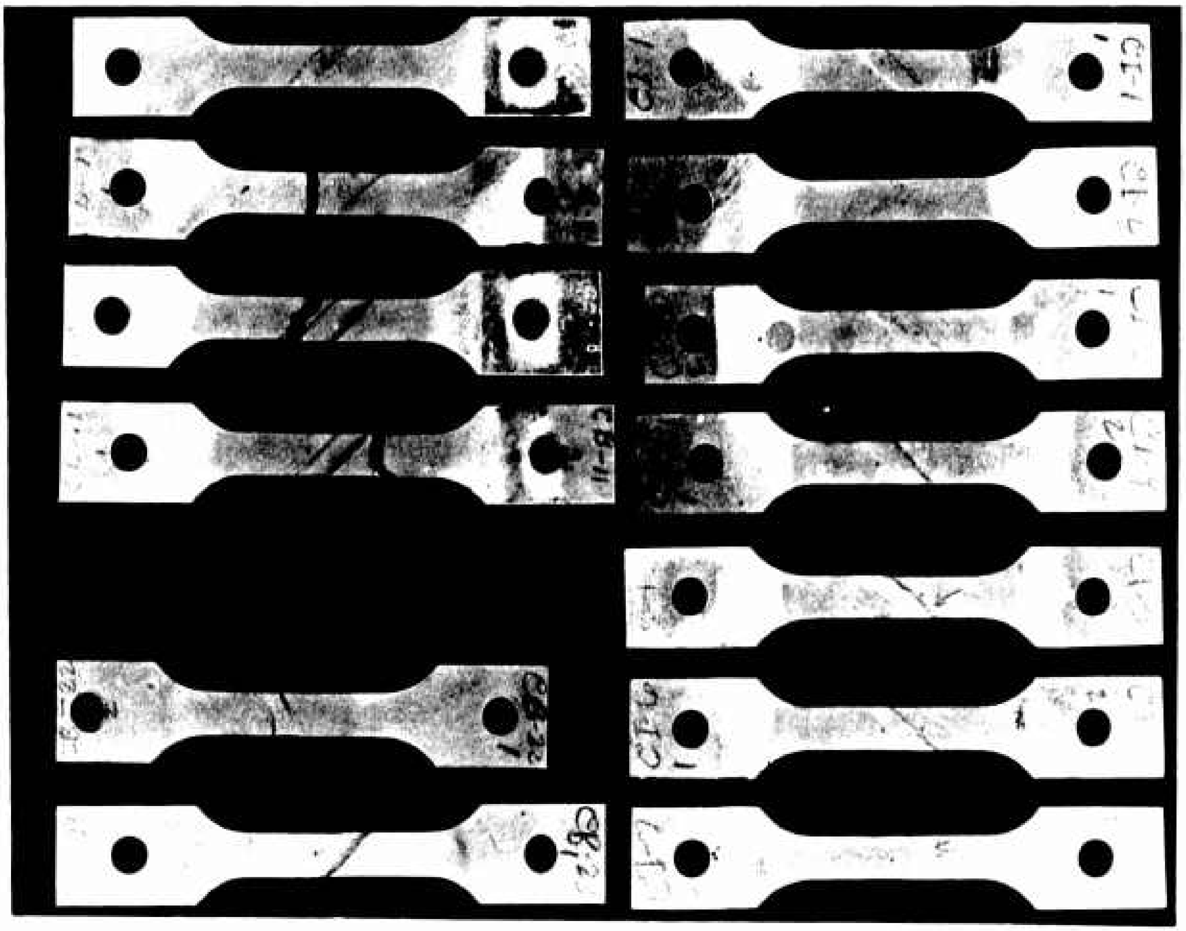


FIGURE 23. Comparison of the Tested Specimens of the Crack Sensitive Heat Number 11 with those of the Crack Resistant Experimental Heat Number 10 which were Subjected to Same Constant Strain Gleeble Testing.

Neg. No. MO 8390-2

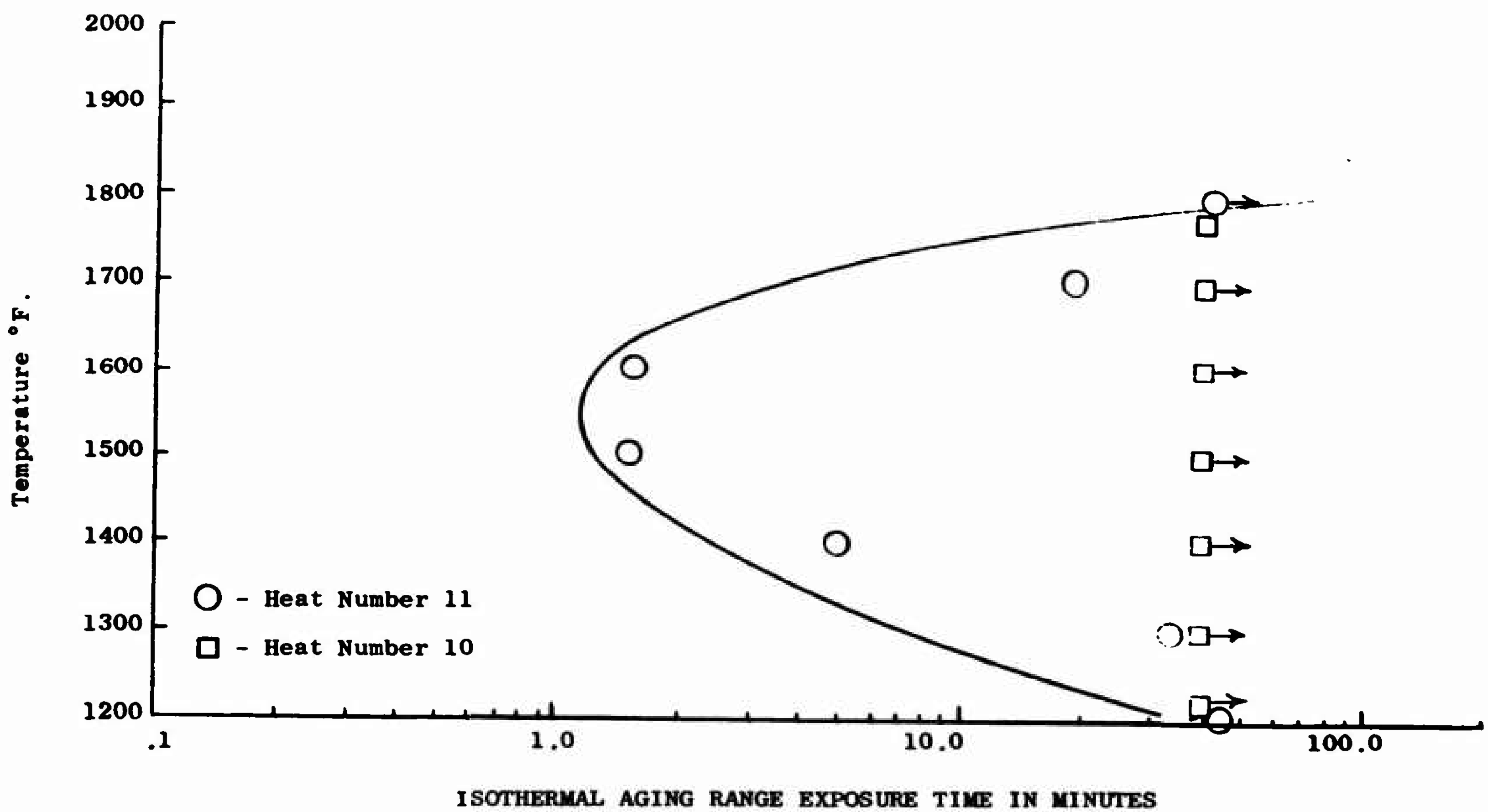


FIGURE 24. Crack Susceptibility C-Curve As Generated by the Constant Strain "Gleeble" Test Procedure Using a Rene' 41 Crack Sensitive Heat Number 11 and Crack Resistant Heat Number 10. Results are shown in Table 3.

for the crack sensitive heat specimen roughly assume a C-shape similar to that of the Type III C-curve with the nose in the 1500° to 1600°F region and times to failure increasing as the extremeties to the aging range was approached. This can be seen by comparison of Figure 24 with Figure 14. Thus, the constant strain "Gleeble" test procedure was also capable of detecting differences in weldability much the same as the circular patch test procedure and the constant load "Gleeble" test procedure.

To further illustrate the correlative relationship between the results obtained by using the "Gleeble" in comparison to the patch test assembly, the crack sensitive and crack resistant heats were made into 90° reduced face TIG welded specimens (Figure 16) and tested using the constant strain "Gleeble" procedure with a constant elongation of 0.030 inch. The results of this testing are shown in Table 4 and graphically in Figures 25 and 26. It can be seen immediately that the crack sensitive heat, Heat Number 11, failed catastrophically at every aging range temperature tested, whereas the crack resistant heat Experimental Heat Number 10, remained intact at every temperature with only fine, tight cracking occurring at the high aging temperatures 1500°F to 1800°F. Many of the specimens of the crack sensitive heat failed during the incremental loading. The shorter times to failure for Heat Number 11, even though the elongation was less was caused by the reduced section of the test specimen forcing the elongation to occur over a shorter gage length (hence, higher strain)

Thus, it can be seen that this testing sequence substantiated previous results by exhibiting the ability of the constant strain "Gleeble"

TABLE 4

RESULTS OF CONSTANT STRAIN GLEEBLE TESTING THE CRACK SENSITIVE AND CRACK RESISTANT HEATS OF RENE' 41

Crack Sensitive Heat - Heat Number 11
Crack Resistant Heat - Experimental Heat Number 10
Constant Elongation Value - 0.30"
Specimen Type - 90°, faced-reduced, TIG

Temp. °F	Exposure Time at Temperature after Full Application of Constant Strain (Minutes)		Initial Stress (ksi)		Final Stress (ksi)		Location of Failure	
	Heat #11	Heat #10	Heat #11	Heat #10	Heat #11	Heat #10	Heat #11	Heat #10
1200	0.1	45.0	95.7	79.6	92.8	78.6	HAZ	None
1300	FOL (2)	45.0	75.7	57.8	----	----	HAZ	None
1400	3.0	45.0	80.0	55.5	76.9	18.0	HAZ	None
1500	FOL (2)	45.0	72.6	81.2	----	56.0	HAZ	HAZ (1)
1600	FOL (2)	45.0	52.9	71.5	----	34.0	HAZ	HAZ (1)
1700	---	45.0	----	54.0	----	18.8	---	HAZ
1800	FOL (2)	45.0	33.6	28.6	----	7.0	HAZ	HAZ

Legend: (1) These failures were small, fine, heat-affected zone cracks which were detected by a flourescent penetrant inspection after the 45 minute time limit.

(2) FOL - Failed-on-loading - These specimens failed during the incremental increase of strain.

Temperature °F	Crack Sensitive Heat	Crack Resistant Heat
1200		
1300		
1400		
1500		
1600		
1700		
1800		

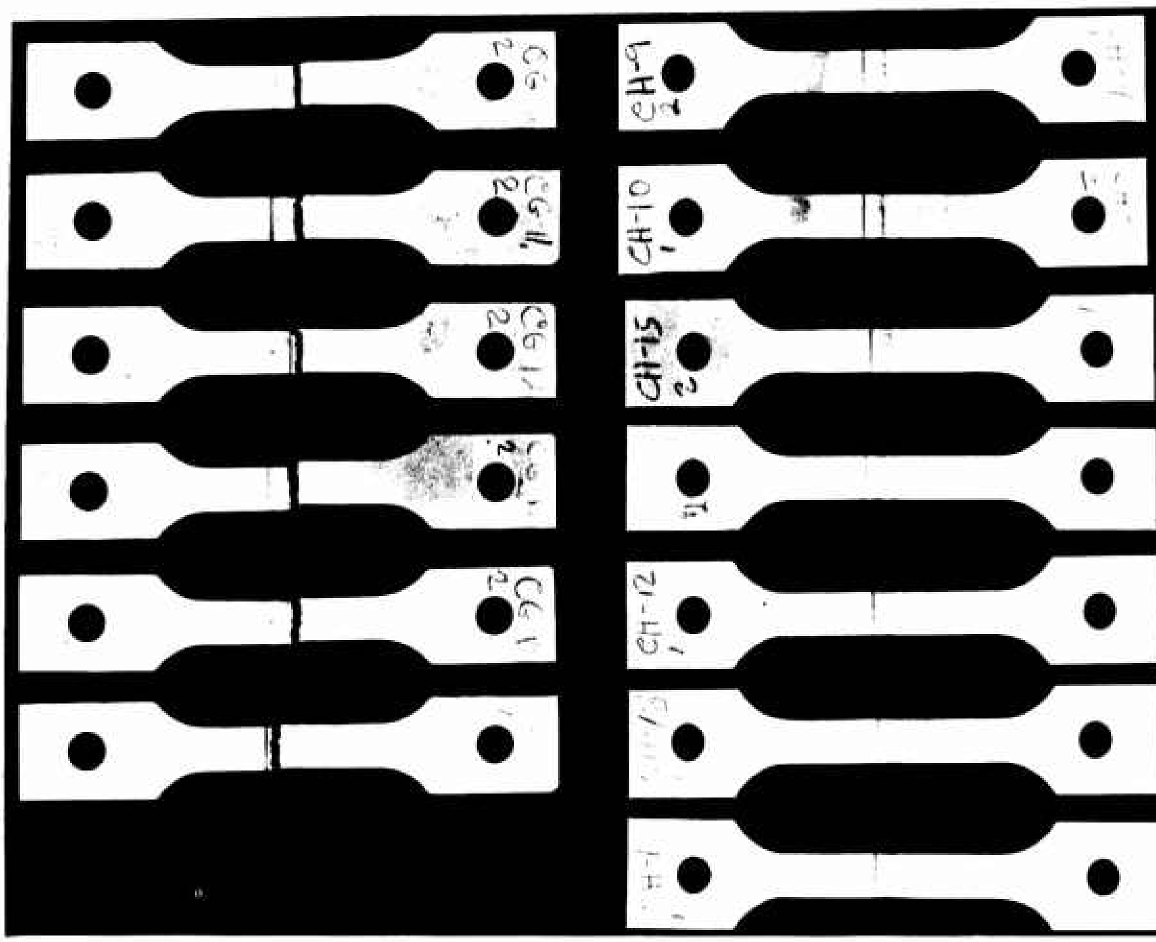


FIGURE 25. Comparison of the Tested Specimens of the Crack Sensitive Heat Number 11 and Crack Resistant Heat Number 10 which were Subjected to the Constant Strain Gleeble Testing.

Neg. No. MO 8390-1

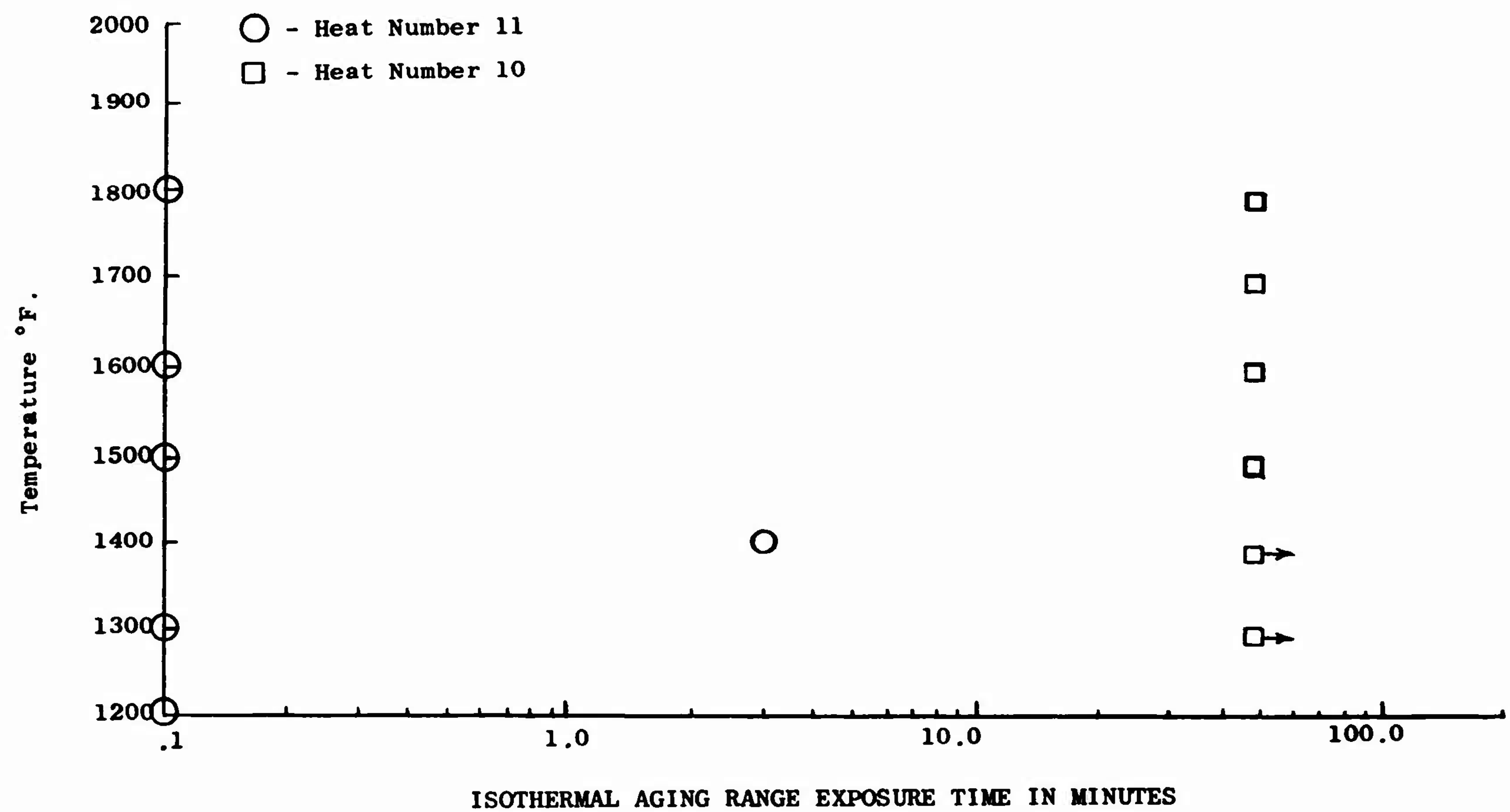


FIGURE 26. Crack Susceptibility C-Curve As Generated by the Constant Strain "Gleeble" Test Procedure Using a Rene' 41 Crack Sensitive Heat Number 11 and Crack Resistant Heat Number 10. Results are shown in Table 4.

technique to distinguish heats of Rene' 41 that are crack sensitive from heats that are crack resistant.

2.3 Base Line Constant Strain "Gleeble" Testing Parameters

Heat Number 10 was chosen to serve as a base line against which the weldability of other heats could be compared. Heat Number 10 was chosen because the first year's evaluation had indicated this heat to have superior weldability. As shown previously, these results were confirmed by both patch testing and constant load "Gleeble" testing. It was the objective of Phase II to further improve the weldability of Rene' 41, so it was appropriate that any further testing be compared to a heat of Rene' 41 with superior weldability.

These base line conditions are presented in Table 5. The constant elongation values in Table 5 were determined by straining the specimens at each selected temperature to a peak initial stress level of 75% of the selected fracture strength of the Rene' 41 alloy. The specimens used for the base line condition are shown in Figure 27.

Use of Heat Number 10 as a base line against which other heats could be compared required that the "Gleeble" specimens of the condition heat to be loaded to a peak initial <u>strain</u> or a peak initial <u>stress</u> corresponding to those of Heat Number 10. It was decided that testing would be conducted using <u>both</u> of these initial conditions. The exact testing procedure selected is outlined below:

1) Heat the specimen to the selected aging temperature, incrementally apply a predetermined elongation (which is sufficient

TABLE 5

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41

HEAT NUMBER 10 BASE LINE CONDITIONS

Test Temperature °F	Constant Elongation (inches)	Peak Initial Stress (ksi)	Final Stress (ksi)	Time To Failure (min)	Crack Location
1200	.175	84.1	79.6	45.0	HAZ
1300	.154	81.1	57.6	4.0	PM
1400	.044	79.0	75.2	3.0	HAZ
1500	.0534	69.4	42.1	45.0	HAZ
1600	.0414	57.3	24.9	45.0	HAZ
1700	.058	44.1	18.5	11.0	
1800	.111	--	21.7	FOL	HAZ

Legend

HAZ - heat affected zone

PM - parent metal

FOL - failed on loading

Base Line Condition

Temperature °F

Specimens

1200

1300

1400

1500

1600

1700

1800

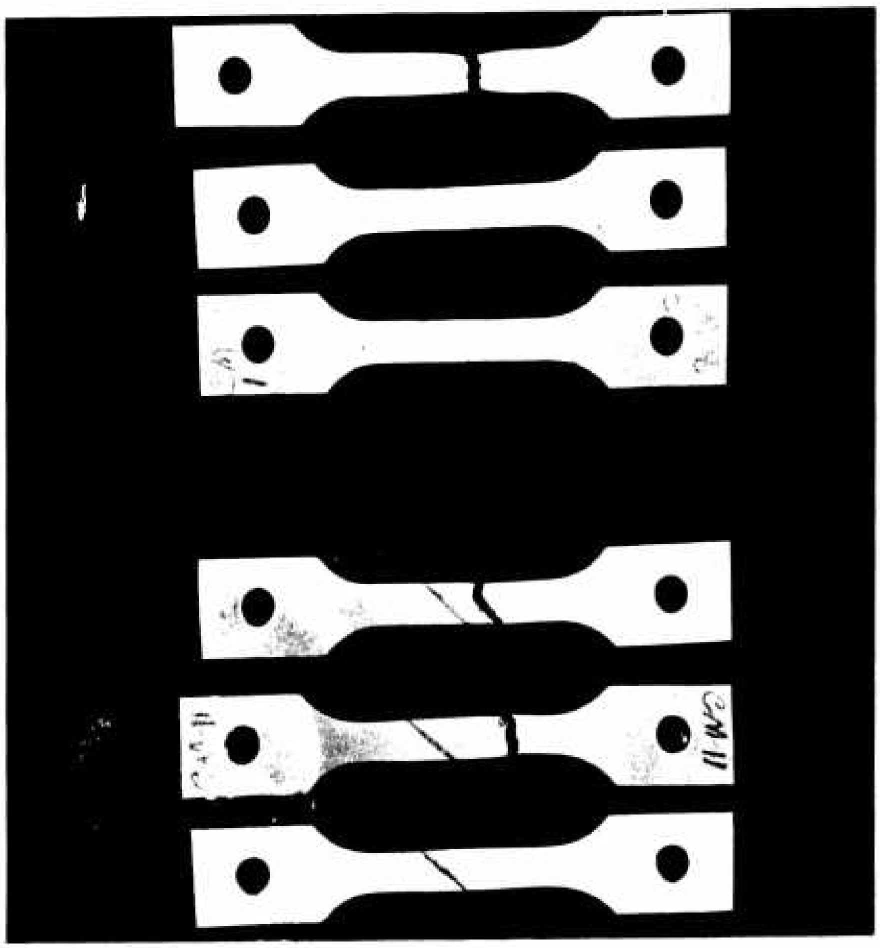


FIGURE 27. Tested Specimens From the Base Line Conditions for Crack Resistant Heat Number 10 Tested With the Constant Strain Gleeble Testing Procedure.

Neg. No. [illegible] 8390-3

to cause strain-age cracking in crack resistant Heat Number 10), the cross head movement, and hold until cracking occurs.

) ... the specimen to the selected aging temperature, incrementally apply a predetermined stress (which is sufficient to cause strain-age cracking in crack resistant Heat Number 10), lock the cross head movement, and hold until cracking occurs.

Testing in this manner required careful interpretation of results. A heat which has lower strength than Heat Number 10 but higher ductility will have shorter failure time using the procedure (2) above than procedure (1). The weldability of this hypothetical heat should be better than Heat Number 10. This reasoning leads to the selection of procedure (1) as the best indication of strain-age crack susceptibility. Further interpretation of results using these two procedures will be given in Phase II.

3.0 Conclusion of Phase I Results

1) A restrained weld "patch" test post weld heat treating procedure (named Type III) was developed which quantitatively measured the time to initiate strain-age cracking occurring during an isothermal arrest in the aging temperature range for precipitation hardened nickel base alloys.

2) Two "Gleeble" test procedures, a constant strain and a constant load, were also developed which could measure differences in strain-age cracking sensitivity.

3) For quantitative measurement of differences in strain-age cracking susceptibility, the constant load "Gleeble" test

procedure is the simplest and fastest testing procedure developed. Its simplicity makes it adaptable to other test equipment and allow a more widespread usage of this procedure as a strain-age crack susceptibility test.

4) The C-curve using the patch test Type III post weld heat treating procedure which defines the isothermal exposure areas which are subject to strain-age cracking, can be used to select the minimum heating rate to the solution treatment temperature for a highly restrained weldment to avoid strain-age cracking.

B. PHASE II

The major objective of Phase II was to use the Type III patch test procedure and the constant strain "Gleeble" procedure established in Phase I to study the effects of chemical composition, heat treating procedures, and other selected variables on the strain-age crack sensitivity of Rene' 41.

1.0 Strain-Age Crack Susceptibility of Rene' 41 Experimental Heats With Variations in Chemical Composition

The General Electric Specification for Rene' 41 is given in Appendix B and includes the chemical composition limits and mechanical property requirements.

Data obtained from the first year's effort[(1)] indicated a trend that lower carbon, iron, silicon, and manganese decreased the susceptibility to strain-age cracking. These data also suggested that the strength of the Rene' 41 as specified in General Electric Specification B50T59 could be maintained with reduced carbon if slight increases in titanium and aluminum were made concurrently.

The variation and addition of several other elements were also investigated. The addition of small amounts of columbium to nickel base alloys have been shown by several investigators to stabilize the titanium carbide, i.e., decrease the propensity to dissolve at elevated temperatures (in excess of 2100°F). Such an addition would be expected to decrease the amount of carbon taken into solution in the weld heat affected zone. Less carbon would, therefore, be available to form the $M_{23}C_6$ carbide during subsequent exposure of the heat affected zone to aging temperatures. This $M_{23}C_6$ carbide is responsible, in part, for the relatively low ductility exhibited by nickel base alloys in this temperature range. Any increased heat affected zone ductility would be expected to increase the resistance to strain-age cracking. One common precipitation hardened nickel base alloy, Inconel 718, which contains columbium does not form the $M_{23}C_6$ carbide and is resistant to strain-age cracking.

The element cobalt has also been documented by several investigators to have an adverse affect on 1400°F tensile ductility -- increased cobalt decreases the ductility. Rocketdyne and others have documented that small magnesium additions to nickel base alloys also increases the 1400°F tensile and rupture ductility. Therefore, the effects of magnesium, columbium, and cobalt were also studied in addition to variations in carbon, iron, silicon, manganese, aluminum, and titanium.

1.1 Material Production and Mechanical Properties

Twenty-one experimental heats of Rene' 41 with variations in carbon, aluminum, titanium, manganese, silicon, iron, magnesium, cobalt, and columbium were selected. The heats were designed statistically in order to gain the most useful information from approximately twenty experimental heats of Rene' 41.

The statistical design also allowed for the random variations which might occur in alloying elements which were selected to be held constant. The experimental heats were vacuum induction melted and processed to 0.060 inch sheet by Allvac Metals Company (Division of Teledyne Corporation) in their Development and Research Facilities. The requested target chemical compositions and actual analysis are presented in Table 6. The analyses were not all within the range requested. However, the discrepancies were small enough that the statistical design of the alloy variations could tolerate them. The mill processing procedure used to produce 0.060 inch sheet was held rigidly constant to avoid introducing processing variables into the several heats. The processing procedure is listed in Appendix C. All heats were rolled to 0.060 inch sheet with no problem except Heat Number 41 (1% columbium, 0.014% carbon) which cracked up during initial hot rolling. The heat was remelted, and initial breakdown was performed with a forge hammer rather than a rolling mill. It also cracked, hence work was discontinued on this composition.

The mill annealed and solutioned and aged (30 minutes at 1975°F, air cooled, 16 hours at 1400°F) room temperature and 1400°F tensile properties were determined using the specimen design shown in Figure 28. The specimens were removed with the rolling direction parallel to the major axis of the tensile specimen. Grain size was determined in each of the heats in the mill annealed and solutioned and aged conditions. The results are presented in Tables 7 and 8. The minimum 1400°F yield strength, as required in the General Electric Company Specification was exceeded by three of the heats. The remaining heats were as much as 22 ksi below the specification minimum of 111.0 ksi.

Stress rupture strength was measured at 1200°F and 1400°F using the tensile specimen design (Figure 28). The material was in the solution treated and aged condition (30 minutes at 1975°F, air cooled, 16 hours at 1400°F).

TABLE 6

CHEMICAL COMPOSITION OF HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

(Analyzed and Certified by Allvac)

Heat No.		Cr	Fe	C	Si	Co	Ni	Mn	Mo	Al	Ti	B	P	S	Cb
23	requested	18.75-19.25	1.5-2.0	.01-.02	.10-.30	10.75-11.25	Bal	.05-.10	9.5-10.0	1.55-1.65	3.25 3.35	.005-.010	.010 max	.010 max	
	actual	19.25	1.93	.014	.20	11.20	Bal	.15	9.85	1.57	3.34	.005	.003	.002	
24	requested	18.75-19.25	1.5-2.0	.01-.02	.10 .30	10.75-11.25	Bal	.05-.10	9.5-10.0	1.35-1.45	3.25-3.35	.005-.010	.010 max	.010 max	
	actual	18.95	1.98	.019	.20	11.25	Bal	.09	10.0	1.47	3.37	.006	.003	.007	
25	requested	18.75-19.25	.2 max	.01-.02	.10 max	10.75-11.25	Bal	.04 max	9.5-10.0	1.75-1.85	2.95-3.05	.005-.010	.010 max	.010 max	
	actual	19.15	.18	.014	.10	10.60	Bal	.02	9.73	1.75	3.11	.005	.005	.003	
26	requested	18.75-19.25	.2 max	.01-.02	.10 max	10.75-11.25	Bal	.04 max	9.5-10.0	1.55-1.65	3.55-3.65	.005-.010	.010 max	.010 max	
	actual	18.75	.05	.014	.09	11.20	Bal	.02	9.87	1.55	3.47	.006	.003	.003	
27	requested	18.75-19.25	1.5-2.0	.03-.04	.10-.30	10.75-11.25	Bal	.05-.10	9.5-10.0	1.75-1.85	3.55-3.65	.005-.010	.010 max	.010 max	
	actual	18.82	1.87	.038	.22	11.20	Bal	.08	10.05	1.78	3.72	.005	.003	.003	
28	requested	18.75-19.25	1.5-2.0	.03-.04	.10-.30	10.75-11.25	Bal	.05-.10	9.5-10.0	1.35 1.45	2.95-3.05	.005-.010	.010 max	.010 max	
	actual	18.95	1.75	.033	.11	11.10	Bal	.06	9.90	1.45	3.02	.007	.004	.002	

TABLE 6 -- continued

CHEMICAL COMPOSITION OF HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Heat No.		Cr	Fe	C	Si	Co	Ni	Mn	Mo	Al	Ti	B	P	S	Cb
29	requested	18.75-19.25	.2 max	.03-.04	.10 max	10.75-11.25	Bal	.04 max	9.5-10.0	1.55-1.65	3.25-3.35	.005-.010	.010 max	.010 max	
	actual	18.85	.10	.003	.07	11.15	Bal	.02	9.85	1.64	3.38	.005	.004	.006	
30	requested	18.75-19.25	.2 max	.03-.04	.10 max	10.75 11.25	Bal	.04 max	9.5-10.0	1.35-1.45	3.55-3.65	.005-.010	.010 max	.010 max	
	actual	18.75	.15	.033	.10	11.05	Bal	.04	9.99	1.48	3.57	.006	.004	.003	
31	requested	18.75-19.25	1.5-2.0	.05-.06	.10-.30	10.75-11.25	Bal	.05-.10	9.5-10.0	1.55-1.45	2.95-3.05	.005-.010	.010 max	.010 max	
	actual	18.85	1.78	.052	.16	11.25	Bal	.08	9.90	1.61	3.03	.005	.004	.002	
32	requested	18.75-19.25	1.5-2.0	.05-.06	.10-.30	10.75-11.25	Bal	.05-.10	9.5-10.0	1.75-1.85	3.25-3.35	.005-.010	.010 max	.010 max	
	actual	18.70	1.80	.052	.17	11.20	Bal	.09	10.00	1.83	3.35	.005	.005	.007	
33	requested	18.75-19.25	.2 max	.05-.06	.10 max	10.75-11.25	Bal	.04 max	9.5-10.0	1.45	3.05	.005-.010	.010 max	.010 max	
	actual	19.14	.10	.052	.11	11.30	Bal	.03	9.89	1.59	3.10	.005	.005	.003	
34	requested	18.75-19.25	.2 max	.05-.06	.10 max	10.75-11.25	Bal	.04 max	9.5-10.0	1.75-1.85	3.55-3.65	.005-.010	.010 max	.010 max	
	actual	18.87	.10	.057	.08	11.25	Bal	.03	9.93	1.76	3.38	.004	.004	.004	

Heat No.		Cr	Fe	C	Si	Co	Ni	Mn	Mo	Al	Ti	B	P	S	Cb
35	requested	18.75-19.25	.2 max	.05-.06	.10 max	0.5 max	Bal	.04 max	9.5-10.0	1.75-1.85	3.55-3.65	.005-.010	.010 max	.010 max	
	actual	18.89	1.95	.014	.30	.10	Bal	.19	9.85	1.56	3.28	.005	.003	.001	
36	requested	18.75-19.25	1.5-2.0	.01-.30	.10-.30	5.5-6.5	Bal	.05-.10	9.5-10.0	1.55-1.65	3.25-3.35	.005-.010	.010 max	.010 max	
	actual	18.93	1.95	.018	.23	6.0	Bal	.10	9.88	1.54	3.24	.005	.003	.001	
37*	requested	18.75-19.25	1.5-2.0	.01-.02	.10-.30	10.75-11.25	Bal	.05-.10	9.5-10.0	1.55-1.65	3.25-3.35	.005-.010	.010 max	.010 max	
	actual	19.05	1.57	.014	.19	11.10	Bal	.09	10.0	1.70	3.38	.005	.006	.001	Mg-.04
38*	requested	18.75-19.25	1.5-2.0	.05-.06	.10-.30	10.75-11.25	Bal	.05-.10	9.5-10.0	1.55-1.65	3.25-3.35	.005-.010	.010 max	.010 max	
	actual	18.75	1.56	.052	.18	11.20	Bal	.09	9.97	1.60	3.29	.006	.006	.001	Mg-.05
39	requested	18.75-19.25	1.5-	.01-.02	.10-.30	11.75-11.25	Bal	.05-.10	9.5-10.0	.05 max	.05 max	.005-.010	.010 max	.010 max	
	actual	19.60	1.98	.219	.07	11.60	Bal	.08	9.53	.05	.05	.007	.004	.002	
40	requested	18.75-19.25	.2 max	.01-.02	.10 max	10.75-11.25	Bal	.04 max	9.5-10.0	1.55-1.65	3.25-3.35	.005-.010	.010 max	.010 max	.4-.6
	actual	18.80	.12	.014	.05	11.05	Bal	.01	9.86	1.58	3.32	.005	.004	.001	.29

TABLE 6 -- continued

CHEMICAL COMPOSITION OF HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

TABLE 6 -- continued

CHEMICAL COMPOSITION OF HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Heat No.		Cr	Fe	C	Si	Co	Ni	Mn	Mo	Al	Ti	B	P	S	Cb
41**	requested	18.75-19.25	.2 max	.01-.02	.10 max	10.75-11.25	Bal	.04 max	9.5-10.0	1.55-1.65	3.25-3.35	.005-.010	.010 max	.010 max	.9-1.1
	actual	18.82	.08	.014	.09	11.18	Bal	.05	9.93	1.57	3.28	.005	.003	.001	1.03
42	requested	18.75-19.25	.2 max	.07-.08	.10 max	10.75-11.25	Bal	.04 max	9.5-10.0	1.55-1.65	3.25-3.35	.005-.010	.010 max	.010 max	.4-.6
	actual	19.35	.10	.071	.07	11.25	Bal	.04	9.94	1.50	3.18	.006	.006	.006	.31
43	requested	18.75-19.25	.2 max	.07-.08	.10 max	10.75-11.25	Bal	.04 max	9.5-10.0	1.55-1.65	3.25-3.35	.005-.010	.010 max	.010 max	.9-1.1
	actual	18.45	.09	.072	.07	11.20	Bal	.02	9.96	1.73	3.58	.009	.004	.007	.92

* Heats Number 37 and 38 have an addition of 0.06% Mg. The magnesium was added as a nickel magnesium master alloy under 1/2 atmosphere of argon immediately before the pour.

** Not used - could not be broken down from ingot.

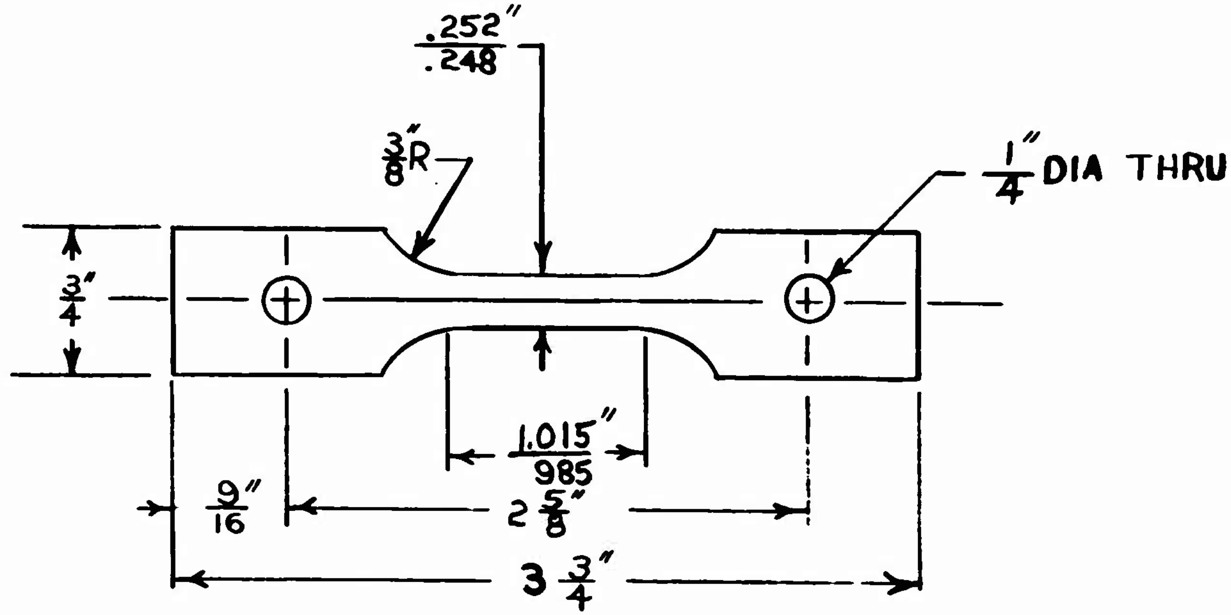


FIGURE 28. Specimens Used for Tensile and Stress Rupture Tests.

TABLE 7

MILL ANNEALED TENSILE PROPERTIES OF RENE' 41 EXPERIMENTAL HEATS

			RT Tensile Properties			1400°F Tensile Properties		
Heat Number	ASTM Grain Size*	Hardness (Rockwell C)	UTS Kpsi	.2% YS Kpsi	Elongation in 1 inch (%)	UTS Kpsi	.2% YS Kpsi	Elongation in 1 inch (%)
10	7	21.7	137.9	70.8	55.5	106.7	89.6	7.1
23	567	17	129	66.0	58	108	99.4	6.5
24	2345	9	124	63.0	60	106	95.3	8.5
25	456	5	120	61.5	63.0	115	100	8.2
26	345	12	123	63.8	25	95.6	88.5	1
27	567	20	142	80.8	47	100	90.7	10
28	3456	6	124	63	58.5	97.4	84.2	9.5
29	456	14	128	95	60.0	110.9	91.6	11.2
30	567	23	145	78.8	36	139	127	3
31	456	8	120.7	56.4	58.0	107.2	83	13.9
32	456	3	127.6	66	64.5	111	95.5	9.0
33	456	17	132	72.2	55	98.4	88	7.5
34	456	17	135	NA	58.0	133.5	NA	24.3
35	3456	19	129	65	47.5	104	95.5	6
36	567	18	132	68	56	107	99.1	4.5
37	345	16	114	52.1	56.5	96.5	86.4	10
38	45	19	137	67.8	50	116	107	5
39	345678	13	112	62	51.5	58.0	37.2	14.5
40	345	15	124	59.1	59	95.5	86.5	7
42	4567	13	136	76.2	42.5	112	102	7
43	5678	19	140	74.8	55	111	103	5

* Predominant grain size is underlined.

TABLE 8

SOLUTIONED AND AGED* TENSILE PROPERTIES OF RENE' 41 EXPERIMENTAL HEATS

Heat Number	ASTM Grain** Size	Hardness (Rockwell C)	RT Tensile Properties UTS Kpsi	RT Tensile Properties .2% YS Kpsi	RT Tensile Properties Elongation in 1 inch (%)	1400°F Tensile Properties UTS Kpsi	1400°F Tensile Properties .2% YS Kpsi	1400°F Tensile Properties Elongation in 1 inch (%)
10	7	41.7	197.5	144.5	21.0	140.2	120.2	4.9
23	13	38	178	110	16.5	124	105	12
24	123	37	180	117	19.5	126	103	4.5
25	124	36.0	169	114.3	40.3	116	98	7.1
26	123	39	193	117	21	128	101	5.5
27	145	42	187	121	18	124	105	15.0
28	134	33.0	164	110	35	110	89	8.4
29	123	35.5	174	119	33.9	118	100	5.5
30	1245	39	167	112	14	133	105	17
31	124	34.5	174	118.5	34	129	98.8	9.5
32	13	36.0	162	128	10	135.5	107	8.0
33	1256	36	181	114	27	135	102	11
34	14	41	184.5	131.5	13.3	146.5	122	7.1
35	23456	39	154	116	9	124	109	7.5
36	13	38.5	179	119	14	132	105	15
37	234	38	176	121	20	132	108	6.5
38	123	39	192	129	18	138	117	6.5
39	23	--	103	38	6.5	43	20.7	13
40	1256	39	184	121	27.5	123	106	5.5
42	123478	41	192	130	21	139	114	9
43	12368	41	192	128	18.5	136	110	7
GE Specification minimum		35	--	--	--	--	111	--

* Solutioned and aged -- 1975°F for ½ hour; 1400°F for 16 hours.

** Predominant grain size is underlined.

TABLE 9

SOLUTIONED AND AGED* STRESS RUPTURE PROPERTIES OF RENE' 41 EXPERIMENTAL HEATS

	1200°F-125,000 psi rupture properties			1400°F-63,000 psi rupture properties		
Heat No.	Failure Time (Hrs)	El in 1" %	Failure Location	Failure Time	El in 1" %	Failure Location
10	29.5	-	Tab	88.2	11.8	Gage
23	5.6	3.5	Gage	154.4	4.4	Gage
24	2.6	3.5	Gage	118.2	4.6	Gage
25	-	10.3	Gage	1.5	-	Tab
26	6.3	4.9	Gage	-	-	-
27	13.5	6.0	Gage	97.7	7.7	Gage
28	1.0	13.8	Gage	23.7	1.2	Gage
29	101.0	11.1	Gage	45.9	1.7	Gage
30	20.8	7.0	Gage	141.4	2.7	Gage
31	1.3	5.1	Gage	39.4	3.4	Gage
32	3.9	4.9	Gage	180.5	6.0	Gage
33	10.0	4.3	Gage	116.0	8.5	Gage
34	7.3	.3	Tab	246.1	5.8	Gage
35	8.1	6.1	Gage	16.0	.9	-
36	4.7	6.1	Gage	185.0	4.3	-
37	32.1	3.6	Gage	69.7	1.8	Gage
38	92.5	3.8	Gage	116.3	37.7	-
39						
40	3.8	6.3	Gage	3.0		-
42	44.1	3.4	Gage	189.3		-
43	26.1	3.6	Gage	147.8	5.2	-
Normal Rene'41 average life	50			50		

* Solutioned and aged - 1975°F for $4\frac{1}{2}$ hour; 1400°F for 16 hours.

The stress was selected to yield 50 hour life for material at the middle of the Rene' 41 stress rupture scatterband. Thus, any specimens lasting 50 hours were as good as the average Rene' 41 strength and lasting 10 hours were within three standard deviations of the average. The results are presented in Table 9. The 1400°F stress rupture properties exceeded the average in twelve of the heats whereas only two heats exceeded the 1200°F stress rupture average strength.

It was concluded that the larger than normal grain size of some of these experimental heats was responsible for the low elevated temperature yield strength and 1200°F rupture strength. The reason(s) for this abnormal grain growth was not readily apparent from a review of their processing history. Nevertheless, all of these heats were evaluated for weldability despite the substandard strengths of some of them.

1.2 Strain-Age Crack Susceptibility of Heats With Variations in Chemical Composition

Each heat was evaluated for susceptibility to strain-age cracking using the constant strain "Gleeble" testing procedure described in Phase I above. Verification of the "Gleeble" test results was performed on several heats using the Type III patch testing procedure also described in Phase I.

"Gleeble" Test Results

The constant strain "Gleeble" test procedure consisted of stabilizing the specimen shown in Figure 20 for 15 minutes at 1000°F, rapidly heating to a preselected aging temperature and slowly (over a 10 to 15 minute period) applying a load to a preselected elongation. The specimen was held at the resultant elongation until failure occurred (maximum holding time 45 minutes). This procedure was repeated over the 1200°F to 1700°F temperature range. This "Gleeble" testing procedure was initially performed using Experimental Heat Number 10 to establish a base line to which all other heats were compared.

The results of the "Gleeble" testing of Experimental Heats 23 to 43 are given in Appendix D. The results are further summarized in Tables 10 and 11.

The most straightforward analysis of the "Gleeble" test results was to examine the extremes in failure times -- 0 to 45 minutes. "Gleeble" test results at these extremes would indicate differences in weldability of the magnitude exhibited by Experimental Heat Number 10 and Production Heat Number 11 (shown previously in Figures 24 and 26). Analysis of Tables 10 and 11 shows that all of these heats fall within the the 0 (zero) to 45 minute range under the selected test conditions. Thus, minor differences in weldability exist between the various heats but nothing with great enough difference (better or worse) to significantly improve or impair the production weldability of Rene' 41.

It was concluded from "Gleeble" testing that no significant differences in strain-age crack susceptibility existed between the heats with variations in chemical composition.

Verification of the "Gleeble" Test Results Using the Patch Test

Several heats were selected for the purpose of correlating "Gleeble" test results with patch test results. Heats were selected on the

TABLE 10

RESULTS OF CONSTANT STRAIN GLEEBLE TESTS ON EXPERIMENTAL RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Time to Failure (minutes) at Indicated Test Temperature
(+ indicates did not fail)

Heat No.	1200F	1300F	1400F	1500F	1600F	1700F
10	<45	4	3	<45	<45	11
23	45+	13.7	21	<45	<48	<45
24	45+	<45	45+	45+	<45	<45
25	<45	3.8	<45	6	<45	FOL
26	14.5	2.5	45+	<45	<45	FOL
27	36	1.8	<45	<45	45+	<45
28	45+	22.5	<45	<45	<45	45+
29	<45	22.6	45+	<45	45+	25
30	<45	3.3	<45	<45	<45	<45
32	48	13	45+	<45	45+	<45
33	45+	12	45+	<45	45+	<45
34	<45	1.1	45+	<45	<45	<45
35	<45		45+		17	
36	45+	16	45+	<45		
37	45+	<45	45+	<45	<45	42
38		19	45+	<45	45+	
40	45+	FOL	45+	33	8.5	FOL
42	<45	6.6	37	<45	<45	<45

Notes on Testing Procedure:

1) Consistant peak initial strain applied to each specimen.
2) Specimen design: Figure 20.

FOL = Failed on loading.

TABLE 11

RESULTS OF CONSTANT STRAIN GLEEBLE TESTS ON EXPERIMENTAL RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

	Time to Failure (minutes) at Indicated Test Temperature (+ indicates did not fail)					
Heat No.	1200F	1300F	1400F	1500F	1600F	1700F
10	<45	4	3	<45	<45	11
23	<45	35.9	9	39	<45	FOL
24	<45	21.6	45+	45+	<45	FOL
25	<45	31	1.4	1	FOL	FOL
26	<45	45+	45+	45+	27	FOL
27	45+	22.9	36.3	<45	<45	4.0
28	<50	9.0	9.0	<45	<45	FOL
29	<45	21.3	45+	<45	<45	FOL
30	45+	29.3	<45	<45	<45	FOL
31	<45	<45	30	<45	<45	30
32	<45	45+	45+	45+	45+	<45
33	<45	<45	25	<45	<45	FOL
34	45+	45+	45+	45+	45+	<45
35	31.3	30	3	15	3.5	FOL
36	<45	32.4	17	FOL	45+	<45
37	<45	32.6	9	<45	<45	
38	45+	<45	45+	45+	<45	45+
40	45+	16.3	21.4	14	9	<45
42	<45	45+	45+	45+	45+	FOL
43	<45	<45	<45	<45	<45	FOL

Notes on Testing Procedure:

1) Consistant peak initial stress applied to each specimen.
2) Specimen design: Figure 20.

FOL = Failed on loading.

basis of being representative of major compositional variations. The heats selected for testing were 26, 29, 33, 36, 38, and 42. These heats were evaluated for weldability using the patch test and the Type III post weld heat treating procedure. The patch test results of these heats are given in Table 12 and are compared with Experimental Heat Number 10 in those time-temperature conditions for which Heat Number 10 was tested.

The results shown in Table 12 are presented in terms of a qualitative evaluation of the amount of cracking that occurred for any particular heat. The cracking classifications were OK for no cracking, and SC for severe cracking. Typical examples of fine cracking and severe cracking are shown in Figures 29 and 30.

It can be seen from Table 12 that there was no clear evidence of crack resistance or crack sensitivity among the various heats tested. The results of Heats 10 and 11 are included to show that the conditions selected would identify a crack sensitive or crack resistant heats. Heat Number 33 appears to be the most crack resistant, but it was not tested at 1300°F and 1400°F for 120 minutes. The patch test results show essentially no difference in crack susceptibility between the six heats. This confirms "Gleeble" results in that the heats with various compositional changes did not yield a substantial improvement in weldability relative to Experimental Heat Number 10.

Additional Studies of Chemical Compositional Effects

The first year's effort indicated the resistance to strain-age cracking could be improved by producing high purity Rene' 41 (essentially low iron, silicon, and manganese). A further verification of this trend was made in Phase I during development of the Type III C-curve heat treating

TABLE 12

RESULTS OF PATCH TESTING FOR THE RELATIVE CRACK SUSCEPTIBILITY OF SEVERAL EXPERIMENTAL HEATS OF RENE' 41 WITH VARIATIONS IN CHEMICAL COMPOSITION

Isothermal Aging Test Conditions										
Temperature (°F)	Time at Temperature (minutes)	10	26	29	33	36	38	42	11
1300	30	OK	FC	OK	OK	FC	--	OK	SC
1300	120	SC	FC	FC	--	--	SC	--	SC
1400	30	OK	SC	SC	FC	SC	SC	SC	SC
1400	120	SC	--	--	--	--	SC	SC	SC
1600	120	OK	FC	SC	OK	SC	OK	SC	SC

Legend

FC - fine cracking

SC - severe cracking

OK - no cracks

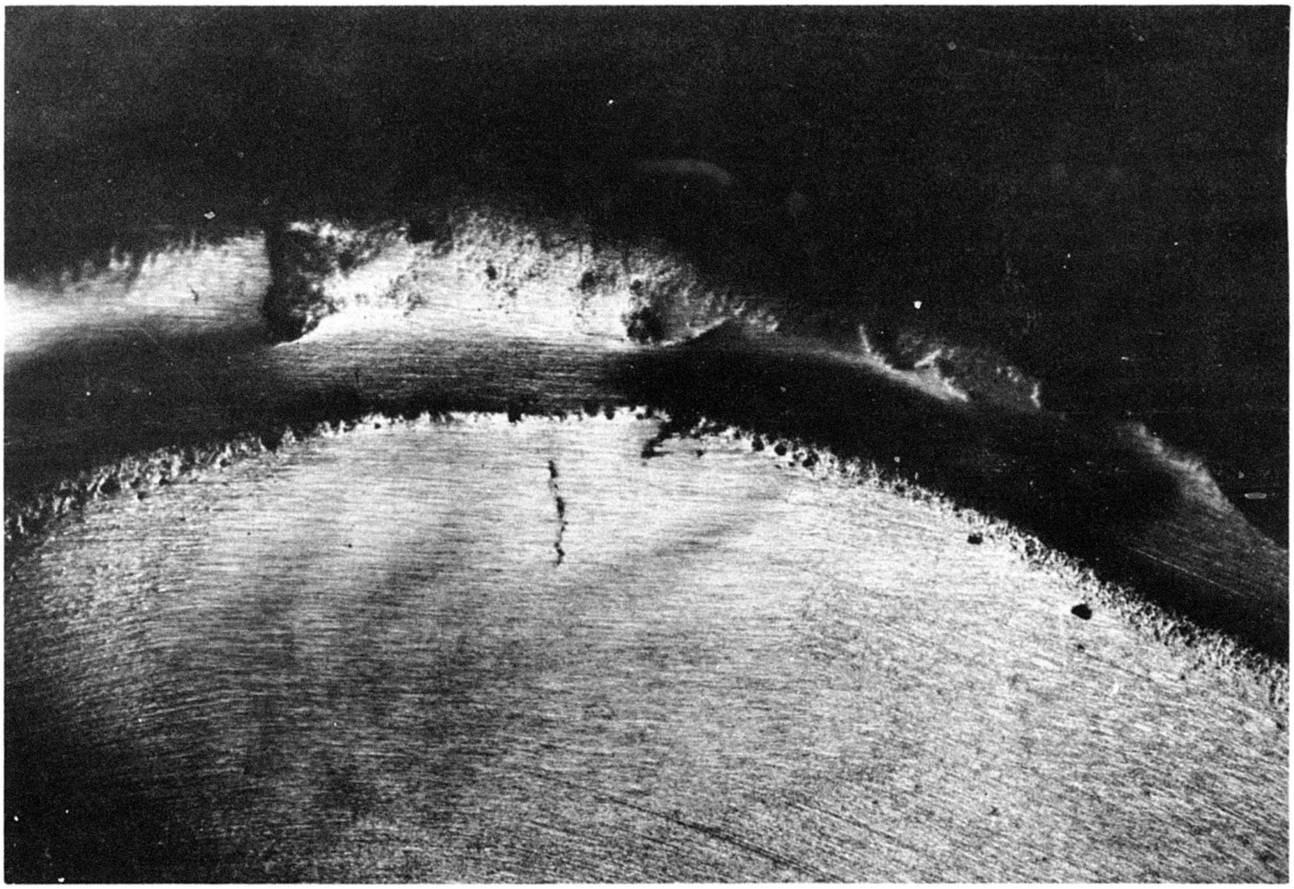


FIGURE 29. Typical Fine Cracking in Patch Test With Type III Post Weld Heat Treatment. Isothermally Aged 30 Minutes at 1300°F. Rene' 41 Experimental Heat Number 26.

Neg. No. 195 Mag: 10 X

FIGURE 30. Typical Severe Cracking in Patch Test With Type III Post Weld Heat Treatment. Isothermally Aged 120 Minutes at 1600°F. Rene' 41 Experimental Heat Number 36.

Neg. No. 228 Mag: 1 X

procedure. This effect is shown in Figure 31 by comparison of the C-curves of two heats of Rene' 41 which are similar in all respects except purity level. This trend was further verified, as will be discussed in Phase III of this program.

2.0 Strain-Age Crack Susceptibility of Rene' 41 With Various Preweld Heat Treatments

Three preweld base metal heat treatments were chosen to be studied for their effect on strain-age crack sensitivity:

1) 2150°F solution heat treatment.
2) 1950°F mill anneal plus age (16 hours at 1400°F).
3) 1975°F solution heat treatment and overaged.

The preweld mill annealed heat treatment (10 minutes at 1950°F, water quench) was used as a base line of comparison.

The effect of these preweld heat treatments on strain-age crack susceptibility was determined primarily with the patch test using the Type III post weld heat treating procedure. The preweld heat treatments that improved the weldability of Rene' 41 were also evaluated using the constant strain "Gleeble" testing procedure.

2.1 2150°F Preweld Solution Heat Treatment

The Rene' 41 sheet was held at 2150°F for one hour in air and air cooled prior to welding. The sheet was then evaluated for susceptibility to strain-age cracking using the patch test with a Type III post weld heat treating procedure. The results are shown in Figure 32. It is apparent

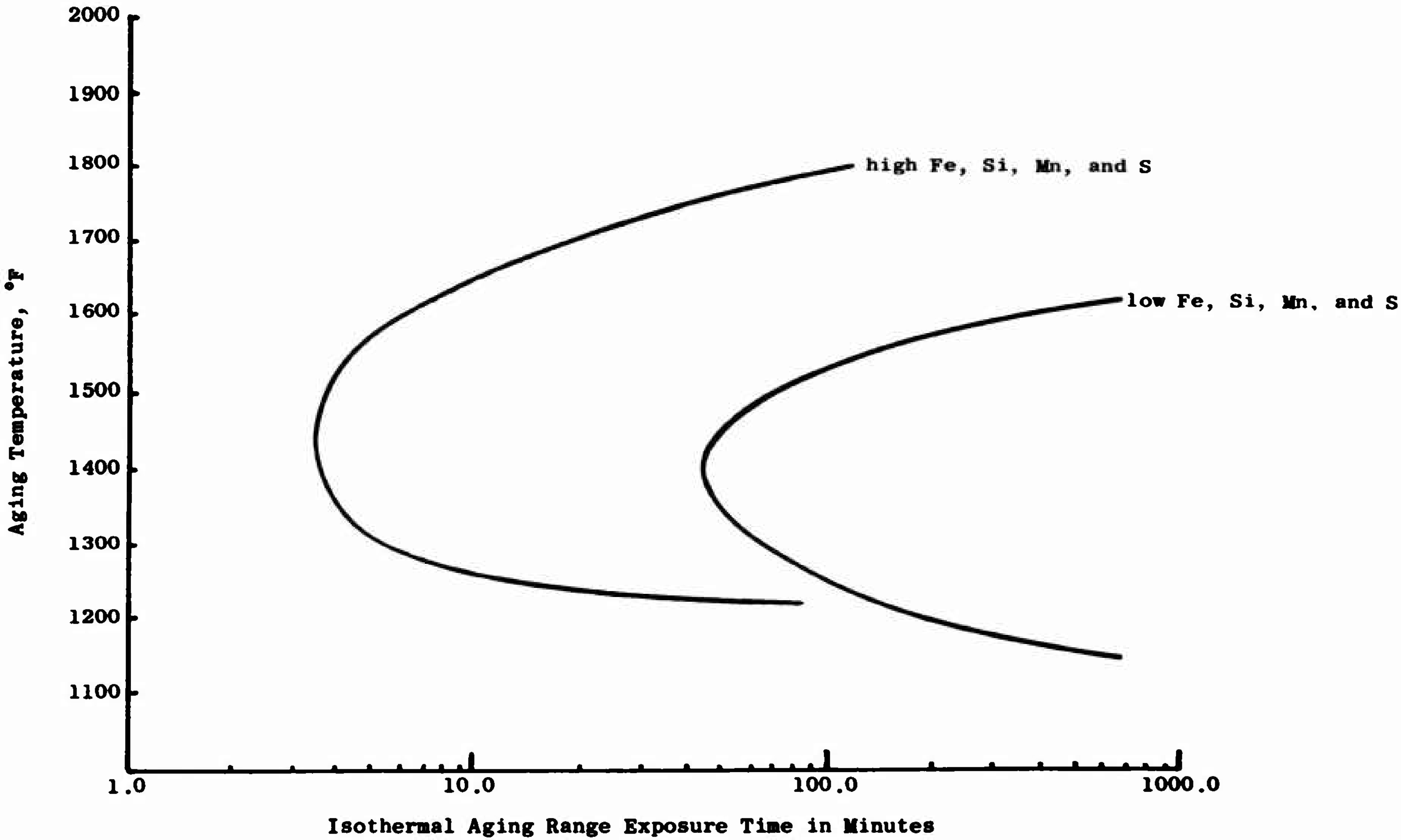


FIGURE 31. Comparison of the Crack Susceptibilities of Two Heats of Rene' 41 With Different Purity Levels. C-curves Generated With The Patch Test Using The Type III Post Weld Heat Treatment for Rene' 41 Heat Number T3-8565. (high Fe, Si, and Mn) and Experimental Heat Number 10 (low Fe, Si, and Mn).

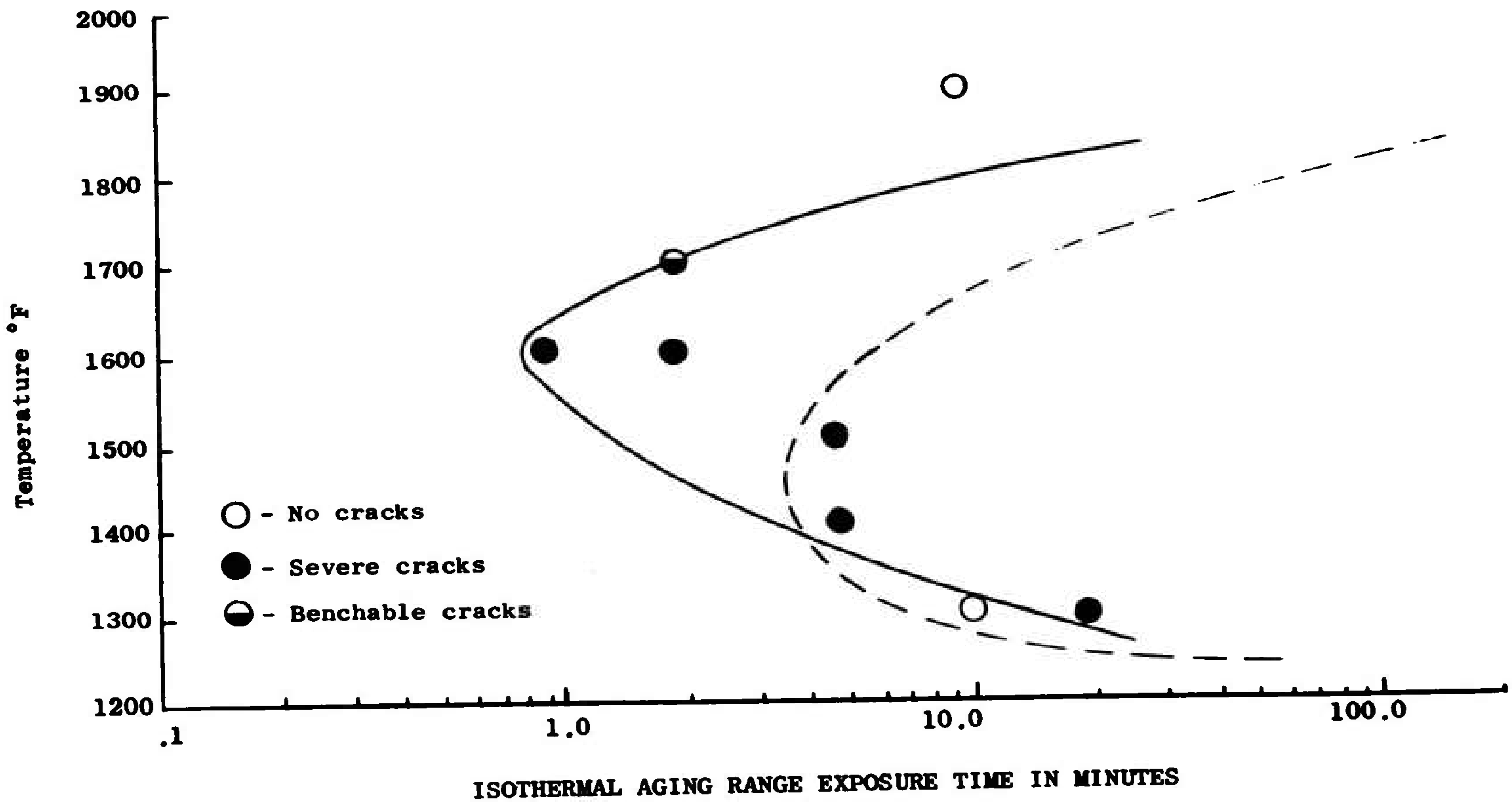


FIGURE 32. Crack Susceptibility C-Curve As Generated by the Patch Test Using the Type III Post Weld Heat Treating Procedure. Rene' 41 Heat T3-3556. Preweld Heat Treatment: 2150°F/1 hour/AC. The dotted curve, shown for comparison, is the C-curve for mill annealed Rene' 41 Heat T3-8565.

that the resistance to strain-age cracking has been markedly impaired by the 2150°F solution heat treatment prior to welding.

2.2 1950°F Mill Anneal Plus 1400°F Age Prior to Welding

Rene' 41 sheet in the mill annealed condition (1950°F for 10 minutes, water quenched) was aged 16 hours at 1400°F prior to welding. Two heats of Rene' 41 were subjected to this preweld heat treatment and evaluated for weldability using the patch test. The results are shown graphically in Figures 33 and 34.

These results indicate essentially no change in sensitivity to strain-age cracking by fully aging prior to welding.

2.3 Overage Preweld Heat Treatment

The overaging heat treatment was selected from previous work conducted at General Electric and consisted of a long time exposure at continuously decreasing aging temperatures as described below:

1) 1975°F for ½ hour, cool at 3 to 8°F/minute to
2) 1800°F, hold for four hours, cool at 3 to 8°F/minute to
3) 1600°F, hold for four hours, cool at 3 to 8°F/minute to
4) 1400°F, hold for 16 hours, air cool to room temperature.

The sheet was evaluated for susceptibility to strain-age cracking using the patch test with a Type III post weld heat treating procedure. The results are shown in Figure 35.

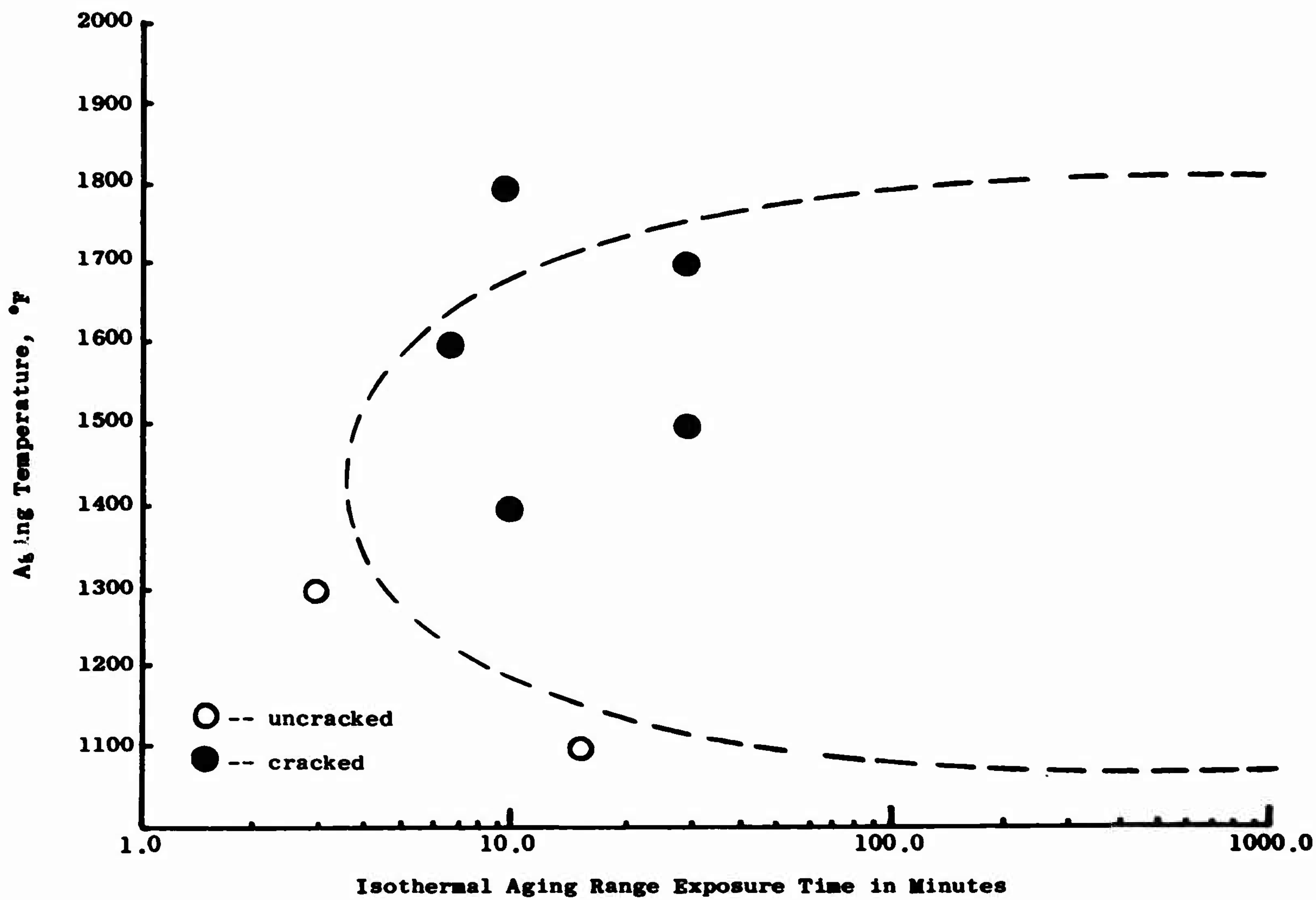


FIGURE 33. Crack Susceptibility C-Curve As Generated by the Patch Test Using the Type III Post Weld Heat Treatment. Rene' 41 Heat Number 11. Preweld Heat Treatment: 1400°F for 16 Hours. The dotted curve, shown for comparison, is the C-curve for mill annealed Rene' 41, Heat Number 11.

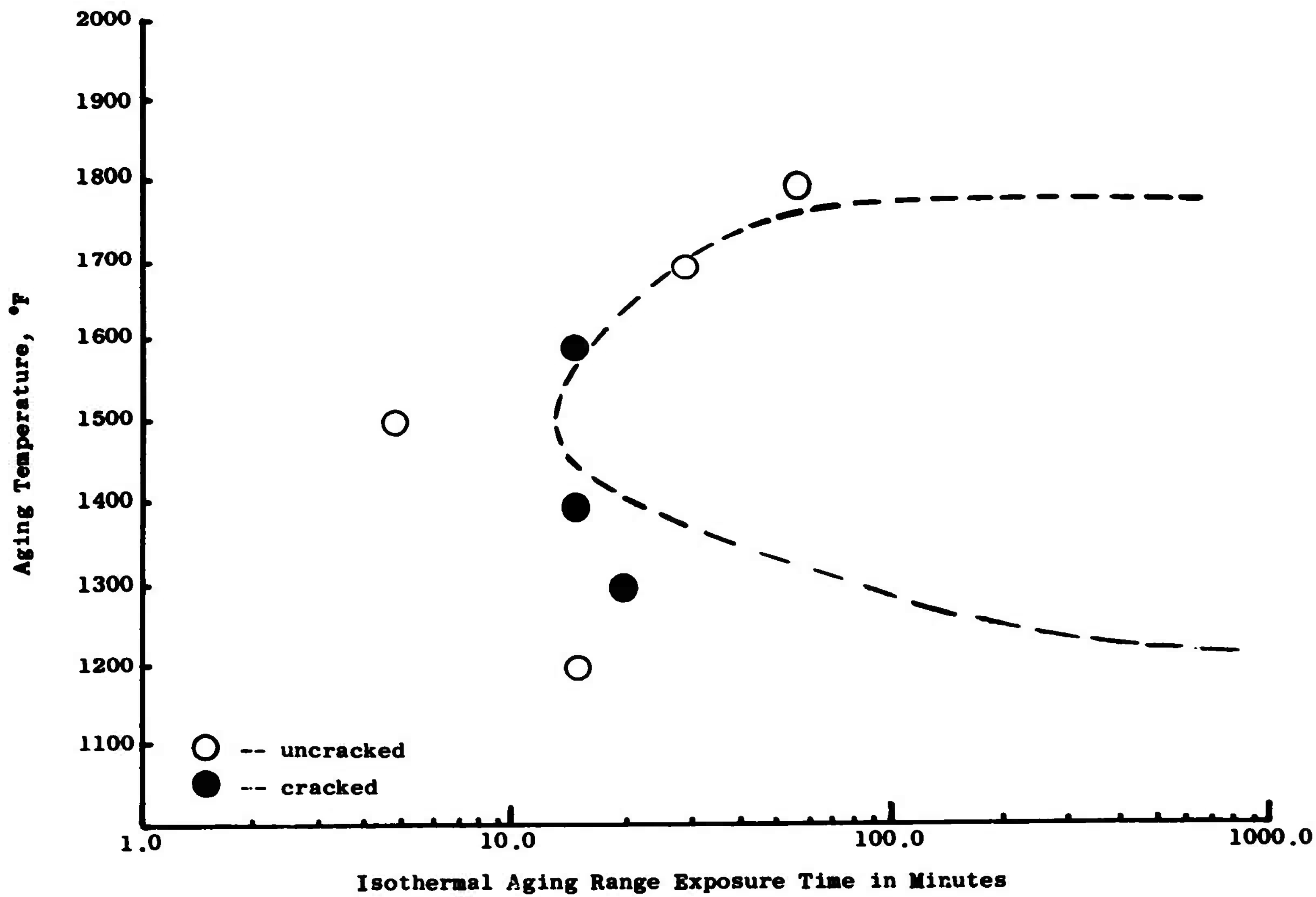


FIGURE 34. Crack Susceptibility C-Curve As Generated by the Patch Test Using the Type III Post Weld Heat Treatment. Rene' 41 Heat T4-8670. Preweld Heat Treatment: 1400°F for 16 Hours. The dotted curve, shown for comparison, is the C-curve for mill annealed Rene' 41, Heat T4-8670.

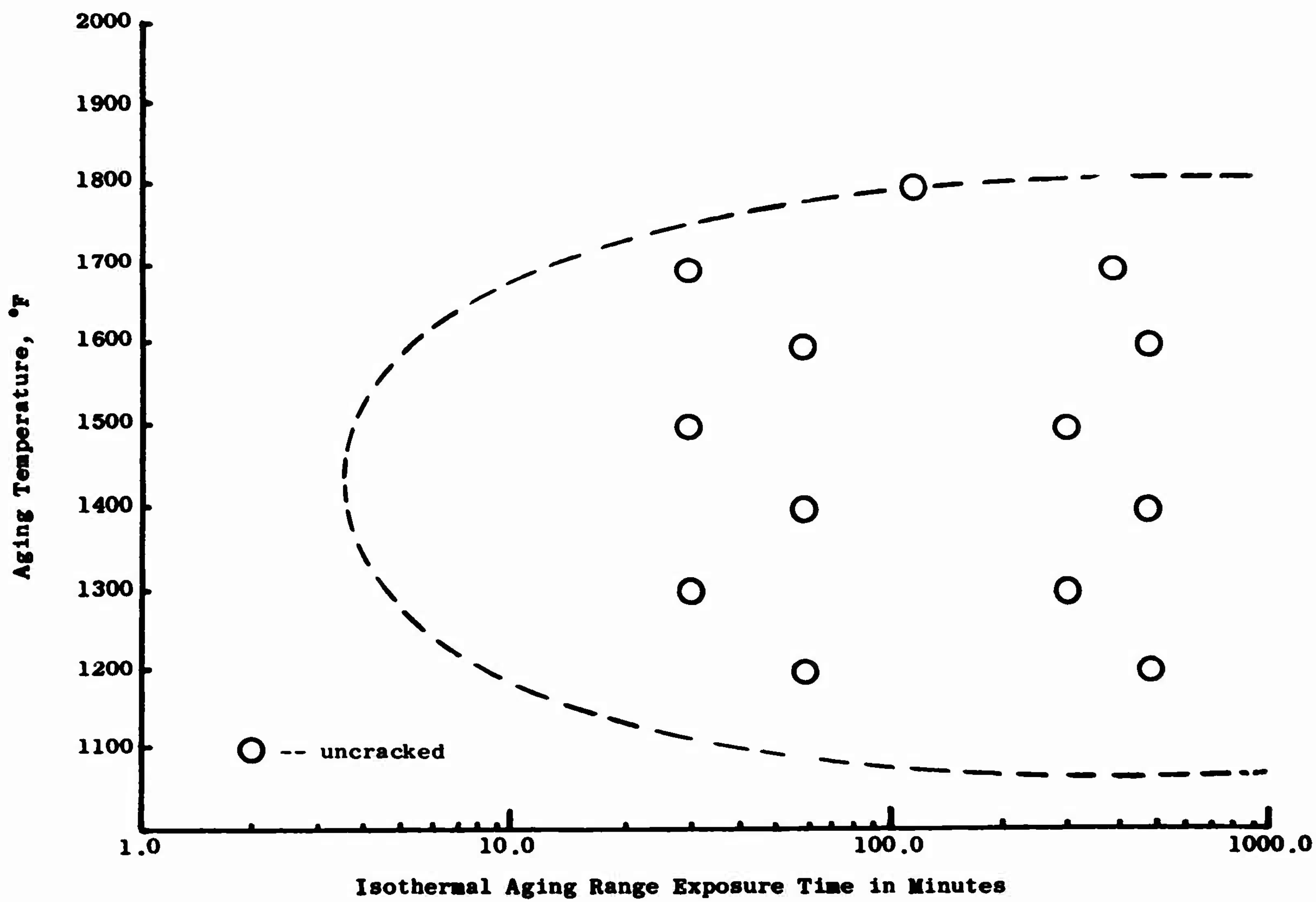


FIGURE 35. Crack Susceptibility C-Curve As Generated by the Patch Test Using the Type III Post Weld Heat Treatment. Rene' 41 Heat Number 11. Preweld Heat Treatment: Overaged. The dotted curve, shown for comparison, is the C-curve for mill annealed Rene' 41 Heat Number 11.

These results show that the overage preweld heat treatment eliminated strain-age cracking during post weld heat treatment of the highly restrained welded Rene' 41 patch test. It should be noted that this heat of Rene' 41 (Heat Number 11) was also the most sensitive to strain-age cracking of all the heats which were evaluated.

With the discovery of this distinct improvement in resistance to strain-age cracking by preweld heat treatment, the effect was also evaluated using the constant strain "Gleeble" testing procedure. The "Gleeble" test results are given in Table 13. These results also indicate the benefit of overaging prior to welding.

3.0 Mechanical and Metallurgical Property Evaluation

Up to this point in the program, the evaluation of weldability had been conducted using several experimental heats of Rene' 41 and three heats from production size quantities. At this time, a Rene' 41 composition was selected for Phase III (Specification Verification). This heat of material incorporated the modifications necessary for improved weldability and was produced in production size quantities. This heat of Material (Allvac Heat 5384) became available concurrently with a portion of the Phase II evaluations and was used in two of the studies -- Effect of Grain Size and Effect of Post Weld Heat Treating Environment.

The chemical composition and tensile and stress rupture properties of the four production heats are shown in Tables 14, 15, 16, and 17. Each heat was similar in chemical composition. However, the strength and ductility of Heat Number 11 was lower than the other three heats.

TABLE 13

RESULTS OF CONSTANT STRAIN GLEEBLE TESTING ON MILL ANNEALED AND OVERAGED RENE' 41, HEAT 11

Pre-Weld Heat Treatment	Test Temperature (°F)	Specimen Elongation (inches)	Peak Initial Stress(ksi)	Time to Failure (min)	Failure Location
MA	1300	.0316	58.5	46.5	PM/HAZ
OA	1300	.0303	58.6	50.0+	DNF
OA	1300	.0319	64.0	45.0+	DNF
MA	1500	.0355	61.4	1.2	PM
OA	1500	.040	61.7	45.0	DNF
OA	1500	.0358	57.2	45.0	DNF
MA	1700	.0338	39.6	45.0	PM
OA	1700	.0471	39.9	45.0	PM
OA	1700	.039	31.3	45.0	DNF

Legend:

DNF - Did not fail
MA - Mill annealed (1950F/10 min, water quench)
OA - Overaged
HAZ - Heat affected zone
PM - Parent metal

Notes on Testing Procedure:

1) Consistent peak initial stress and strain applied to each specimen.
2) Specimen design: Figure 20.

TABLE 14

CHEMICAL COMPOSITION OF PRODUCTION HEATS OF RENE' 41

	CHEMICAL COMPOSITION												
Heat Number	Cr	Fe	C	Si	Co	Ni	Mn	Mo	Al	Ti	B	P	S
5384	18.60	.60	.071	.10	11.20	Bal	.03	9.95	1.47	3.11	.005	--	.005
11	19.02	.30	.07	.06	10.84	Bal	.04	9.84	1.45	3.18	.0056	.06	.006
T3-3556	20.10	2.03	.089	.25	11.55	Bal	.05	10.17	1.60	3.17	.0056	--	.016
T3-3565	19.73	2.03	.067	.18	11.12	Bal	.05	10.09	1.60	3.10	.0045	--	.020

TABLE 15

MILL ANNEALED TENSILE PROPERTIES OF RENE' 41 PRODUCTION HEATS

			RT Tensile Properties			1400°F Tensile Properties		
Heat Number	ASTM Grain Size	Hardness (Rockwell C)	UTS Kpsi	.2% YS Kpsi	Elongation in 1 inch (%)	UTS Kpsi	.2% YS Kpsi	Elongation in 1 inch (%)
5384	7	25.0	154.0	83.6	48.0	119.0	103.0	4.5
			149.0	31.1	50.0	115.0	98.3	7.0
11	1 to 2		149.0	91.3	48.8	92.6	88.8	3.8
T3-8556	7	19.0	134.9	75.0	55.4			
T3-3565	7	16.0	130.0	66.7	61.0			

TABLE 16

SOLUTIONED AND AGED* TENSILE PROPERTIES OF RENE' 41 PRODUCTION HEATS

Heat Number	ASTM Grain Size	Hardness (Rockwell C)	UTS Kpsi	.2% YS Kpsi	Elongation in 1 inch (%)	UTS Kpsi	.2% YS Kpsi	Elongation in 1 inch (%)
5384	7	42.5	202.0	131.0	23.5	144.0	117.0	7.5
			119.0	142.0	20.0	135.0	111.0	5.5
11	1	36.5	143.0	122.0	3.6	115.6	101.9	3.5
T3-3556	7	41.0	193.8	145.0	19.0			
			192.2	147.0	16.4			
T3-8565	7	38.0	184.8	133.7	19.7			
			184.2	136.0	17.9			
GE Specification minimum		35	--	--	--	--	111.0	

* Solution and age - 1975°F for ½ hour;
1400°F for 16 hours.

TABLE 17

SOLUTIONED AND AGED* STRESS RUPTURE PROPERTIES OF RENE' 41 PRODUCTION HEATS

Heat Number	1200°F-125,000 psi Stress Rupture Properties: Failure Time (hours)	1200°F-125,000 psi Stress Rupture Properties: Elongation in 1 inch (%)	1200°F-125,000 psi Stress Rupture Properties: Failure Location	1400°F-63,000 psi Stress Rupture Properties: Failure Time (hours)	1400°F-63,000 psi Stress Rupture Properties: Elongation in 1 inch (%)	1400°F-63,000 psi Stress Rupture Properties: Failure Location
5384	51.1	--	tab	115.6	17.0	gage
	85.1	2.9	gage	123.3	10.0	gage
11	0.5	1.8	gage	7.3	0.6	gage
Normal Rene' 41 Average Life	50			50		

* solution and age - 1975°F for ½ hour; 1400°F for 16 hours.

3.1 Mechanical Properties of Overaged Rene' 41

Several mechanical properties of overaged Rene' 41 were determined to provide insight into the mechanism of improvement in strain-age crack resistance provided by overaging prior to welding. The extent to which mechanical properties could be restored after overaging was also determined. The overage which was used for these mechanical property studies varied slightly from that used in the weldability study. A continuous slow cool from the solutioning temperature was used rather than the interrupted slow cool previously described in Section 2.3. The continuous slow cool provided a more practical production heat treating practice and experience at Rocketdyne[3] had indicated that this preweld heat treatment dramatically reduced the incidence of strain-age cracking in highly restrained welded components.

Hardness and tensile properties of mill annealed and overaged Rene' 41 are given in Tables 18 and 19.

Tensile and stress rupture properties of welded joints in Rene' 41 after overaging and solutioning and aging are given in Tables 20, 21, and 22.

The pertinent results of these tables are briefly summarized below. Items 1 through 4 are compared to properties of Rene' 41 solutioned at 2050°F and aged at 1650°F. This heat treatment is utilized to obtain maximum rupture properties in Rene' 41 at temperatures in excess of 1400°F. The 1975°F solution treatment plus a 1400°F/16 hour age is utilized to achieve maximum tensile properties below 1400°F.

1) Properties in overaged Rene' 41 welded with Hastelloy X, Hastelloy W, or Rene' 41 filler wire can be completely restored by a solution (2050°F) and age (1650°F) provided the weld bead reinforcement is maintained on Hastelloy X and Hastelloy W welds. The Rene' 41 filler can be removed or left on without affecting properties. (This indicates very little effect from the weld bead as a stress concentration. It also indicates that heat affected zone properties after a solution and age are comparable to those of the base metal). See Tables 20, 21, and 22.

2) Removing the weld bead reinforcement on welds made with Hastelloy X and Hastelloy W filler metal lowers the strength of the welded joint to the strength of the diluted fusion zone.

3) Directly aging (1650°F/4 hours) without solution treatment after overaging results in a 25% loss in 1400°F yield strength, and an 8% decrease in 1650°F rupture strength. This procedure nearly doubles (increase from 8% to 14%) 1400°F rupture ductility remain essentially unchanged. See Tables 20, 21, and 22.

4) Overaged Rene' 41 has one half the ductility and 10% higher room temperature yield strength than mill annealed Rene' 41 so it would be less formable. Severe forming should therefore be performed prior to overaging. See Table 19.

TABLE 18

HARDNESS AND GRAIN SIZE OF RENE' 41 HEAT 5384 AFTER VARIOUS HEAT TREATMENTS

Heat Treatment*	Hardness (Rockwell C)	Grain Size (ASTM #)
MA	25.0	7
MA + S_1 + A_1	34.5	1
MA + S_2 + A_2	42.5	7
MA + OA_1	33.0	1 to 7
MA + S_1 + A_1 + OA	32.0	1 to 2
MA + S_1 + A_1 + OA_2	32.5	--
MA + S_1 + A_1 + OA + A_1	29.5	2 to 3
MA + S_1 + A_1 + OA_1 + A_1	34.5	2 to 3
MA + S_1 + A_1 + OA_1 + S_2 + A_1	36.0	2 to 3
MA + OA_1 + S_1 + A_1	35.0	--

<u>Legend</u>

MA - mill anneal, 1950°F/10 minutes, water quench

S_1 - 2050°F/½ hour, AC

S_2 - 1975°F/½ hour, AC

A_1 - 1650°F/4 hours, AC

A_2 - 1400°F/16 hours, AC

OA_1 - 1975°F/½ hour, cool @ 50°F/hour to 1350°F, AC

OA_2 - 2050°F/½ hour, cool @ 100°F/hour to 1000°F, AC

TABLE 19

ROOM TEMPERATURE AND 1400°F TENSILE PROPERTIES OF MILL ANNEALED AND OVERAGED RENE' 41 HEAT 5384

Heat Treatment	Test Temperature °F	UTS Ksi	.2% YS Ksi	Elongation (%)	Failure Location
MA	RT	154	83.6	48	gage
	RT	149	81.1	50	gage
MA + OA_1	RT	174	90.4	22.5	gage
	RT	169	90.4	21.5	gage
	RT	172	90.9	24.0	gage
MA	1400	119	103	4.5	gage
	1400	115	98.3	7	gage
MA + S_1 + A_1 + OA_1	1400	115	72.5	16.5	gage
	1400	107	70.0	20	gage
	1400	112	70.8	20	gage
MA + S_1 + A_1 + OA_2	1400	104	71.3	24.0	gage
	1400	106	69.3	15.5	gage
	1400	103	73.8	17.0	gage

Legend

MA - mill anneal 1950°F/10 minutes, water quench
OA_1 - 1975°F/½ hour, cool 50°F/hours to 1350°F, AC
S_1 - 2050°F/½ hour, AC
A_1 - 1650°F/4 hours, AC
OA_2 - 2050°F/ ½ hour, cool @ 100°F/hour to 1000°F, AC

TABLE 20

1400°F TENSILE PROPERTIES OF WELDED JOINTS IN RENE' 41 HEAT 5384

Heat Treatment*	Test Temperature °F	UTS Ksi	.2% YS Ksi	Elongation (%)	Failure Location
MA + S_1 + A_1	1400	132	100	14	gage
	1400	135	101	15	gage
	1400	134	103	17	gage
MA + W + S_1 + A_1	1400	132	102	12.5	¼" from fusion line
	1400	128	102	12.0	¼" from fusion line
	1400	131	104	11.0	¼" from fusion line
MA + W + grind weld flush + S_1 + A_1	1400	127	103	12.0	¼" from fusion line
	1400	132	107	11.0	¼" from fusion line
	1400	136	108	12.5	¼" from fusion line
MA + OA_1 + W + S_1 + A_1	1400	128	107	10.0	¼" from fusion line
	1400	133	109	10.0	¼" from fusion line
	1400	132	108	8.0	¼" from fusion line

Legend

MA - mill annealed (1950°F/10 minutes, water quench).

W - TIG weld using Rene' 41 filler.

S_1 - solution heat treatment 2050°F/½ hour, AC.

A_1 - age @ 1650°F/4 hours, AC.

OA_1 - 1975°F/½ hour cool @ 50°F/hour to 1350°F/ AC.

TABLE 21

1400F/65.0 Ksi STRESS RUPTURE PROPERTIES IN WELDED JOINTS OF RENE' 41. HEAT 5384

Heat Treatment*	Rupture Life (hrs.)	Elongation (%)	Failure Location
MA + S_1 + A_1	169.2	10	Gage
	114.0	6	Gage
	155.0	8	Gage
MA + W + S_1 + A_1	109.5	8	1/4" from fusion line
	115.8	4	Fusion line
	127.0	7.5	1/2" from fusion line
MA + W + grind weld flush + S_1 + A_1	111.5	5.0	1/4" from fusion line
	125.1	7.0	1/2" from fusion line
MA + OA_1 + W + S_1 + A_1	126.2	5.0	Fusion line
	113.1	5.0	Fusion line
	110.2	3.1	Fusion line

* Legend

MA = Mill annealed (1950F/10 min, water quench)
W = TIG weld using Rene' 41 filler
S_1 = Solution heat treatment 2050F/1/2 hr., AC
A_1 = Age @ 1650F/4 hrs., AC
OA_1 = 1975F/1/2 hr., cool @ 50F/hr. to 1350F, AC

TABLE 22

1650F/25.0 Ksi STRESS RUPTURE PROPERTIES IN WELDED JOINTS OF RENE' 41. HEAT 5384

Heat Treatment*	Rupture Life (hrs)	Elongation (%)	Failure Location
MA + S_1 + A_1	71.4	19	Gage
	117.6	14.5	Gage
	64.2	12	Gage
MA + W + S_1 + A_1	25.1	14.5	3/16"-3/8" from fusion line
	62.4	13.0	3/16" from fusion line
	31.7	17.0	1/4" from fusion line
MA + W + grind weld bead flush + S_1 + A_1	65.0	10.0	Weld and fusion line
	53.4	9.7	Fusion line
	51.2	11.2	Weld
MA + OA_1 + W + S_1 + A_1	52.0	7.0	3/8" from fusion line
	45.0	5.0	1/8" from fusion line
	50.2	6.3	1/8" from fusion line

* Legend

MA = Mill annealed (1950F/10 minutes, water quench)
W = TIG weld using Rene' 41 filler
S_1 = 2050F/1/2 hr. AC
A_1 = 1650F/4 hr. AC
OA_1 = 1975F/1/2 hr. cool @ 50F/hr. to 1350F, AC

3.2 Microstructural Evaluation

The general structure of Rene' 41 heats 11 and 5384 are shown in Figures 36 and 37. These two heats are representative of crack sensitive and crack resistant Rene' 41. The difference in grain size between the two heats is readily apparent.

The discovery of a preweld overaging heat treatment which markedly increased resistance to strain-age cracking led to the examination of the heat affected zone and base metal microstructure in an attempt to correlate microstructural changes with strain-age crack susceptibility. The heat affected zone microstructures of Rene' 41 as-welded after direct aging, and after solution and aging, are shown in Figures 38, 39, 40, and 41.

The heat affected zone (HAZ) microstructures immediately adjacent to the fusion line were examined at higher magnification since this was the region where strain-age cracking predominantly occurs. The electron microscope allowed this region of the HAZ to be examined up to 10,000 X magnification. Typical microstructures immediately adjacent to the fusion line in the as-welded, directly aged, and solutioned and aged conditions are shown in Figures 42 and 43. Both the mill annealed and overaged preweld heat treated conditions are included for direct comparison. The base metal microstructure in the overaged and solutioned and aged conditions are shown in Figure 44.

These structures show that overaging Rene' 41 by slow cooling from the solution temperature produces large globular gamma prime but no noticeable difference in carbide morphology from the mill annealed structure.

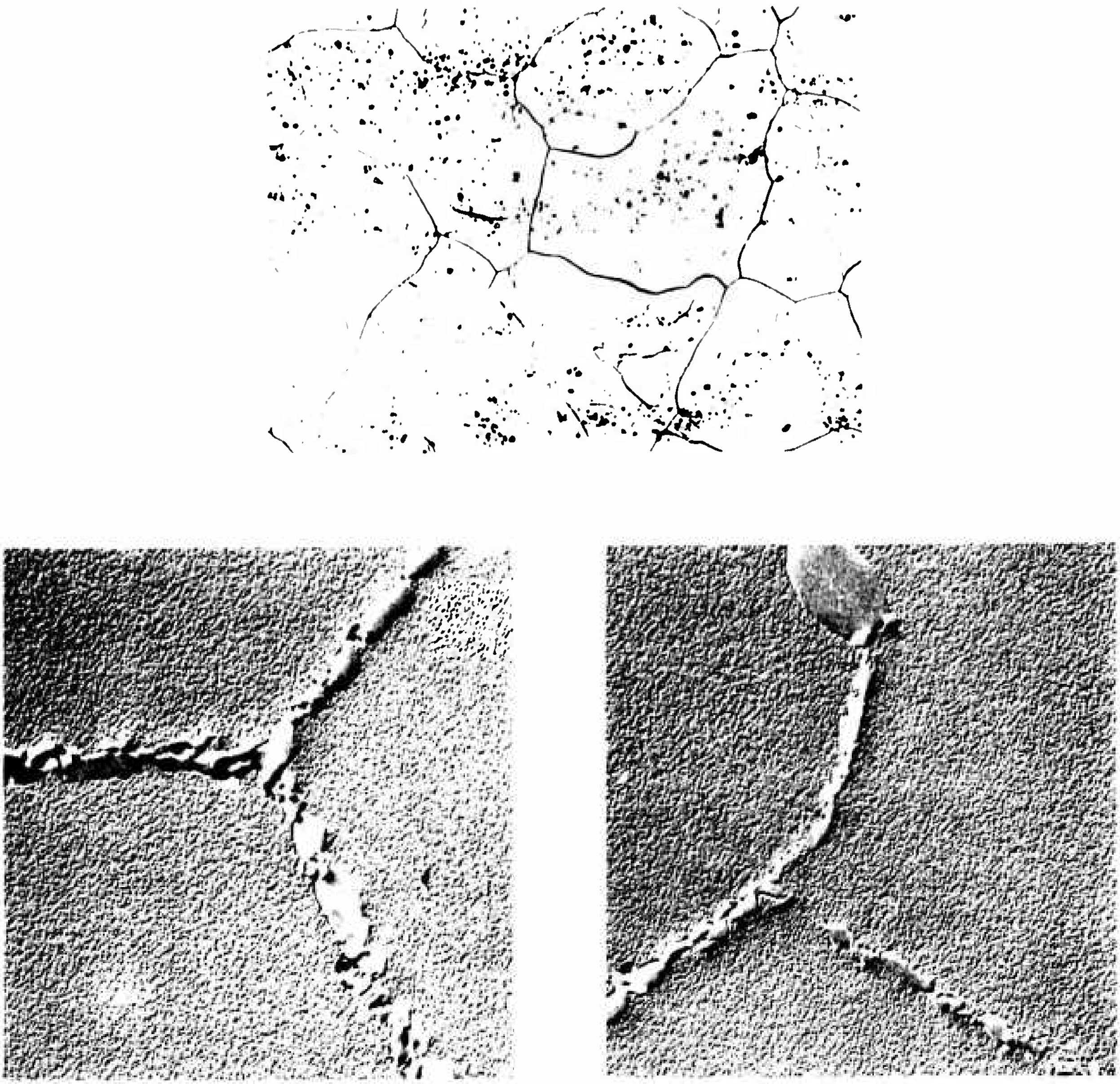


FIGURE 36. General Microstructure of Rene' 41 Heat Number 11 After Solution and Age (1975°F for ½ Hour; 1400°F for 16 Hours)

Neg. Nos. N4769
789A

Mag: (top) 100 X
(bottom) 10,000 X
Etch: HCl and HNO_3

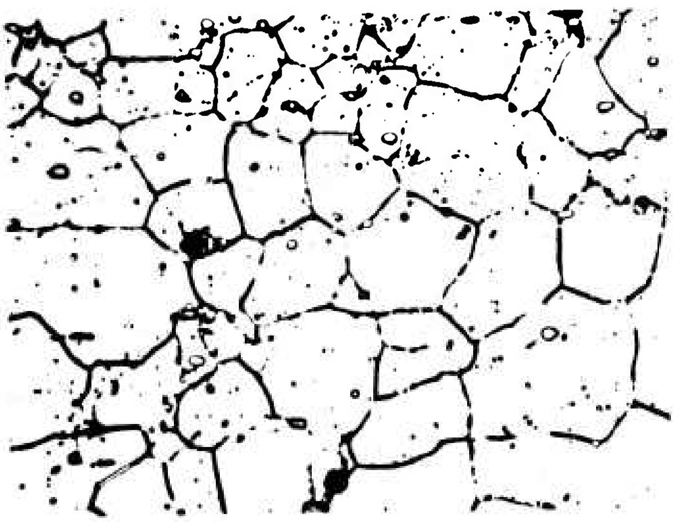


FIGURE 37. General Microstructure of Rene' 41 Heat 5384 After Solution and Age (1975°F for ½ Hour; 1400°F for 16 Hours)

Neg. Nos. N8177 N8185

Mag: (top) 100 X (bottom) 500 X

Etch: HCl and HNO_3

HAZ weld

FIGURE 38. As-Welded Heat Affected Zone Microstructure, Overaged Prior to Welding. Rene' 41 Heat 5384.

Neg. No. N8189

Mag: 100 X
Etch: HCl and HNO_3

FIGURE 39. Heat Affected Zone Microstructure Directly Aged (1650°F for 4 Hours) After Welding, (Overaged Prior to Welding). Rene' 41 Heat 5384

Neg. No. H9677

Mag: 70 X
Etch: HCl and HNO_3

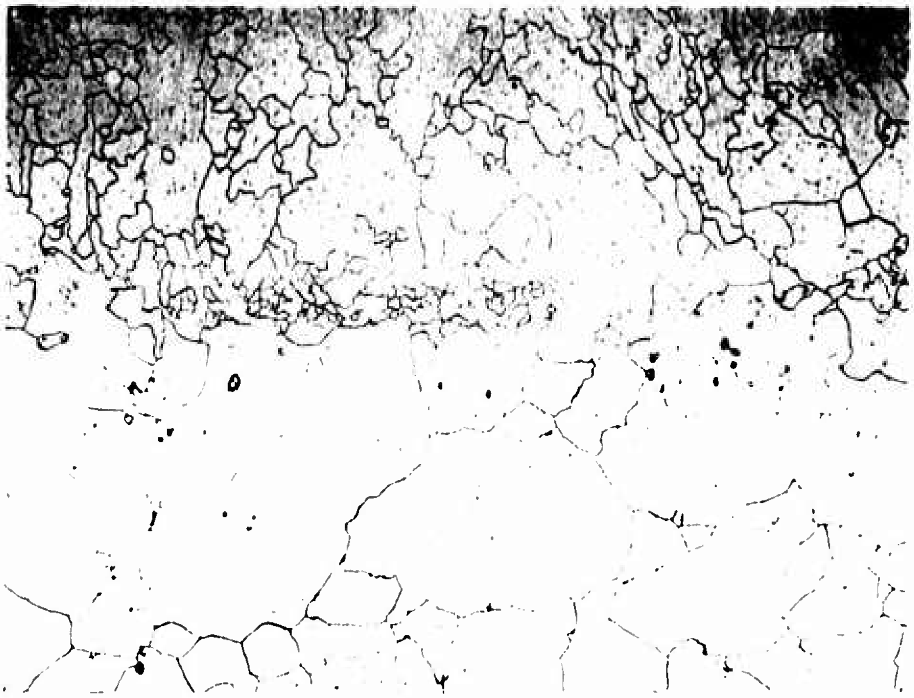


FIGURE 40. Heat Affected Zone Microstructure, Solutioned and Aged (2050°F for ½ Hour, 1650°F for 4 Hours) after Welding; Overaged Prior to Welding.

Neg. Nos. N8187 Mag: (top) 100 X
N8186 (bottom) 500 X
Etch: HCl and HNO_3

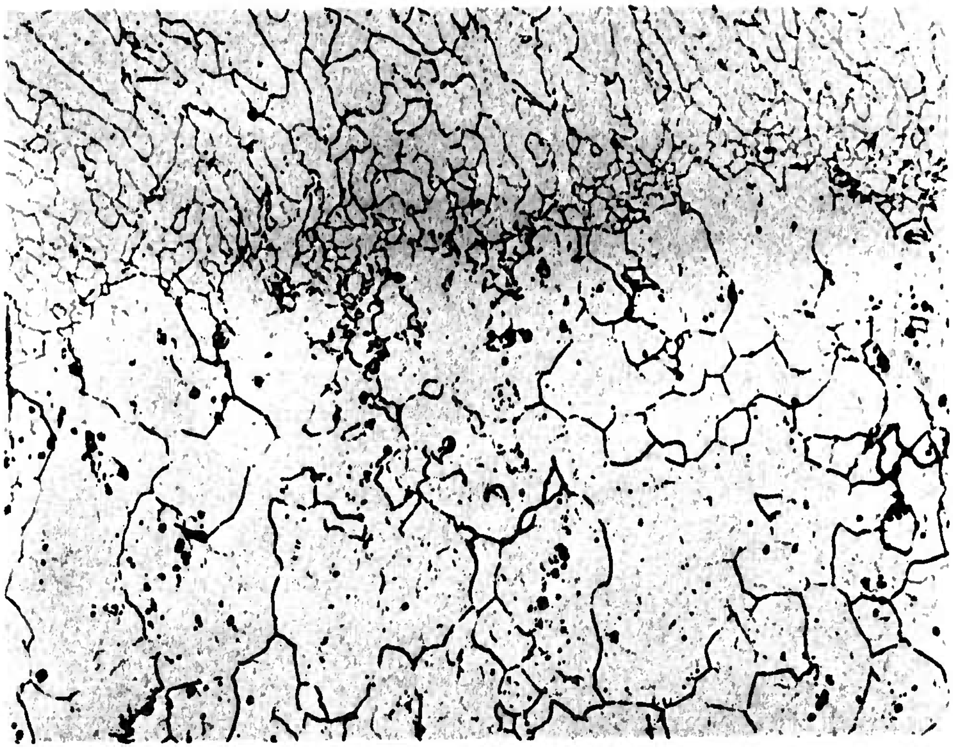


FIGURE 41. Heat Affected Zone Microstructure, Solutioned and Aged (2050°F for ½ Hour, 1650°F for 4 Hours) after Welding; Mill Annealed Prior to Welding.

Neg. No. N8331

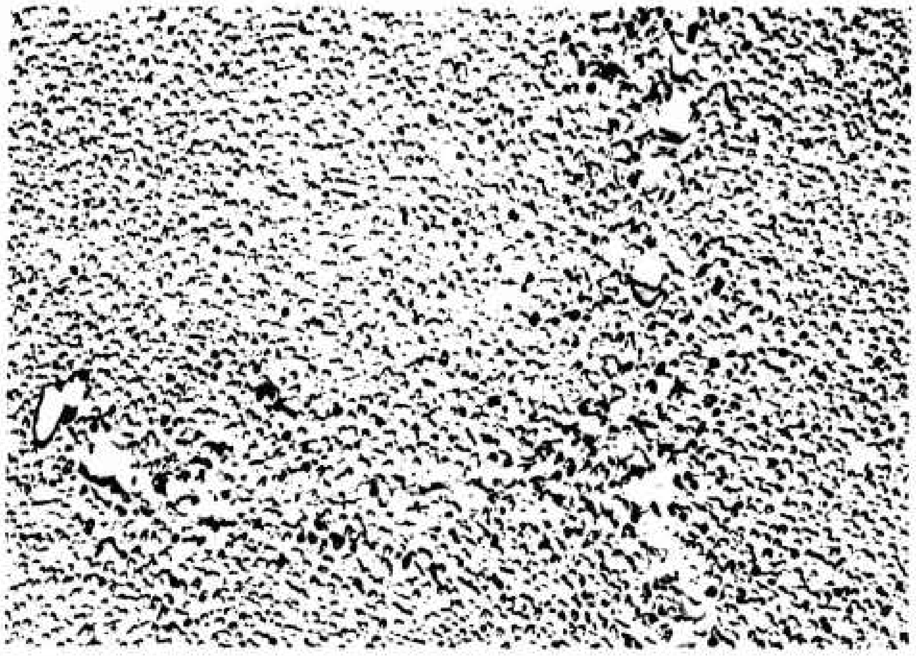
Mag: 70 X
Etch: HCl and HNO_3

mill annealed prior to welding

overaged prior to welding

FIGURE 42. As-Welded Heat Affected Zone Immediately Adjacent to the Fusion Line. Rene' 41 Heat 5384

Neg. Nos. F1528 362-20 Mag: 10,000 X



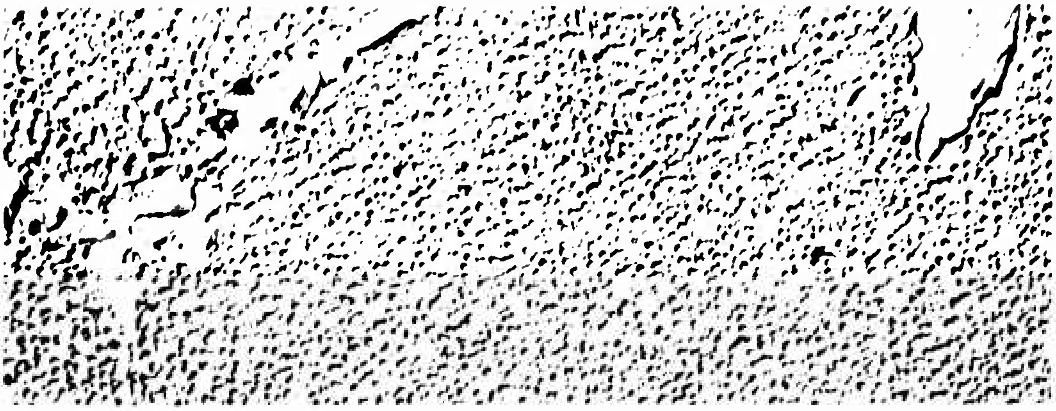
mill annealed prior to welding

overaged prior to welding

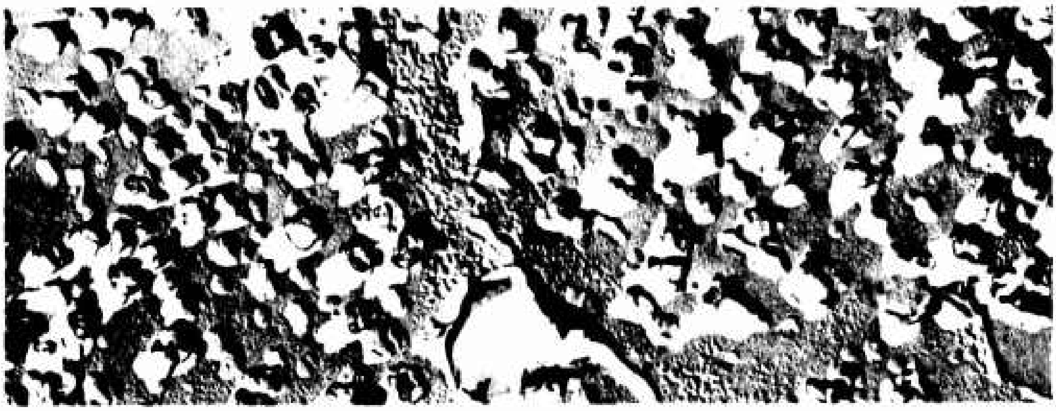
FIGURE 43. Heat Affected Zone Immediately Adjacent To the Fusion Line in Rene' 41 Heat 5384 After Solution and Age (2050°F for ½ Hour; 1650°F for 4 Hours)

Neg. Nos. 363-23
363-27

Mag: 10,000 X



solutioned and aged
(2050°F for ½ hour; 1650°F for 4 hours)



overaged

overaged plus solutioned and aged

FIGURE 44. Rene' 41 (Heat 5384) Base Metal Microstructure In the Overaged and Fully Heat Treated Conditions.

Neg. Nos. 365-5
362-23
363-29

Mag: 10,000 X

The HAZ microstructures show that the region immediately adjacent to the fusion line (within 0.010 inch) is completely solutioned regardless of the preweld base metal heat treatment. This can be seen by comparing the two microstructures shown in Figure 42.

The HAZ structures also show that the microstructure produced by overaging can be completely eliminated by a full heat treatment (solution and age). This is shown in both Figures 43 and 44.

3.3 Aging Response of Rene' 41 Solutioned at 1975°F and 2150°F

The increased sensitivity of the 2150°F solutioned Rene' 41 to strain-age cracking led to speculation of the mechanism involved. Several differences exist between Rene' 41 solutioned at 2150°F and 1975°F -- grain size is larger in 2150°F solutioned material and more of the carbides are in solution. It was speculated that these differences caused a reduction in the aging rate and voluminous carbide precipitation in the grain boundaries.

Aging response of 1975°F and 2150°F solutioned Rene' 41 0.060 inch sheet was determined in the following manner. Strips of Rene' 41 in each condition were held for ½ hour and 8 hours in a gradient furnace. The gradient furnace provided a convenient means of exposing the material to several temperatures within the aging range. Rockwell C hardness measurements were then conducted along the length of the strip. The results are presented in Table 23 and Figure 45 as Rockwell C hardness versus an aging parameter. These results show a small but consistent trend -- the material solutioned at 1975°F aged at a higher rate than the 2150°F solutioned materials. The effect was more pronounced at the shorter aging times. This confirmed that the aging rate was decreased by increasing the solutioning temperature.

TABLE 23

HARDNESS VERSUS AGING PARAMETER FOR 0.060 INCH RENE' 41 IN THE 1975°F AND 2150°F SOLUTIONED CONDITION

Aging Time (minutes)	Aging Temperature °F	Aging Parameter $T(20 + \log t) \times 10^{-3}$	Hardness (Rockwell C)	
			Solutioned at 1975°F	Solutioned at 2150°F
30	1210	32.6	23.5	--
30	1260	33.5	24.3	--
30	1315	34.6	24.7	--
30	1350	35.2	25.5	21.7
30	1405	36.3	35.8	26.8
30	1465	37.5	35.0	31.1
30	1520	38.3	36.6	32.7
30	1560	39.3	37.3	33.9
30	1600	40.1	38.5	33.8
480	1100	32.6	21.2	--
480	1155	33.8	25.1	--
480	1210	34.9	26.1	21.8
480	1260	35.9	27.7	26.8
480	1315	37.1	33.4	30.8
480	1350	37.8	35.3	34.0
480	1405	39.0	39.6	36.2
480	1465	40.3	41.7	37.7
480	1520	41.4	38.1	37.7
480	1560	42.2	39.0	36.1
480	1600	43.0	37.5	35.8

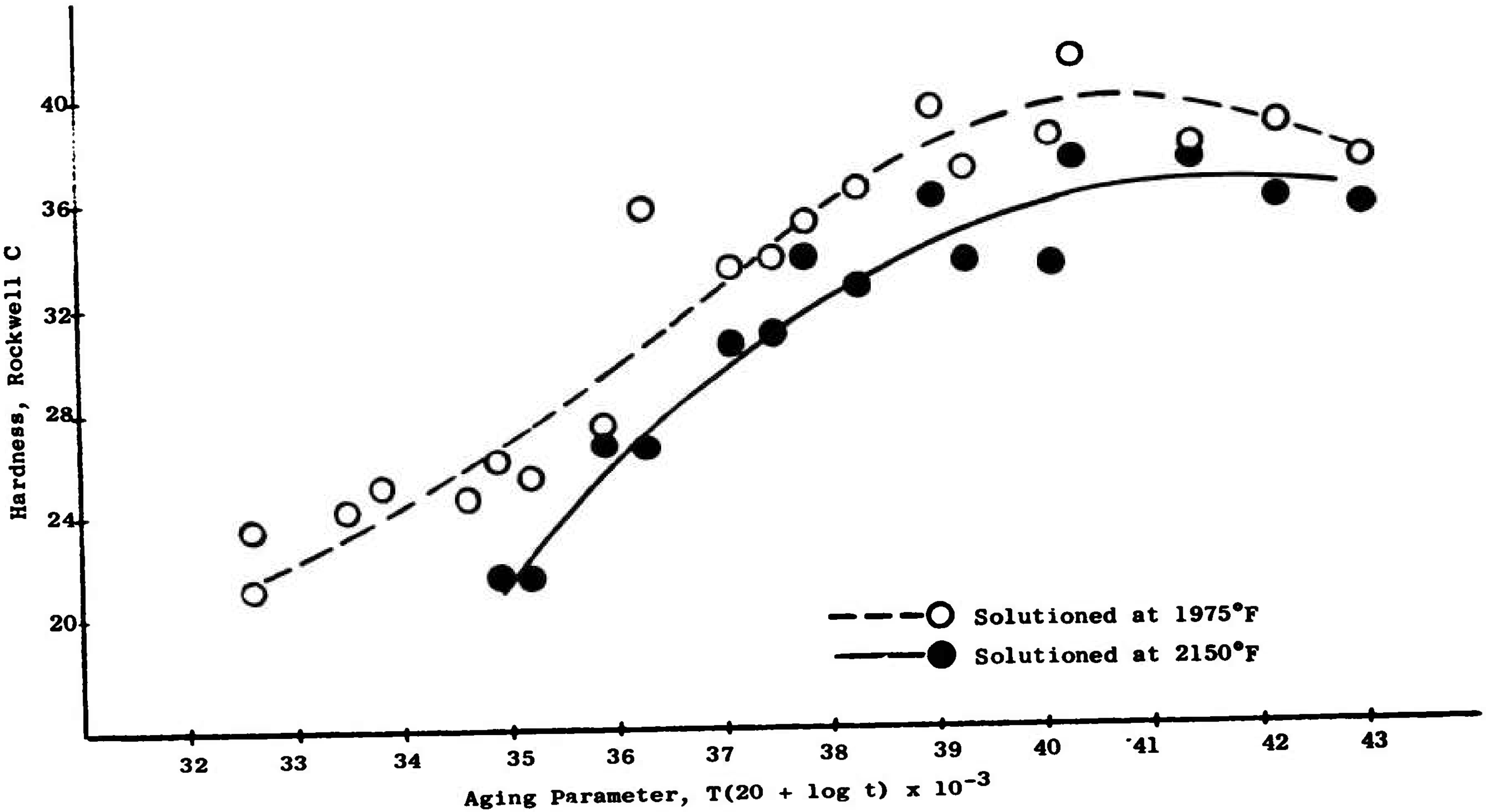


FIGURE 45. Aging Response of Rene' 41 0.060 Inch Sheet in the 1975°F and 2150°F Solutioned Condition.

3.4 Aging Response of Rene' 41 in the Presence of Stress

There was some question whether the residual welding stresses would increase the aging rate or lower the temperature at which aging would occur in Rene' 41. Following is a summarization of aging rates determined in stressed and unstressed mill annealed 0.060 inch Rene' 41.

Sheet metal tensile specimens of mill annealed Rene' 41 (Heat 2495-8182) were exposed to 1, 16, and 30 hours at 1100, 1200, 1300, and 1400°F in a stress rupture furnace with an applied stress of 62,600 psi. The applied stress was the room temperature 0.02% yield strength of this heat of mill annealed Rene' 41. Unstressed coupons, 1 inch by 1 inch, were attached to the stressed specimens so they would be exposed to identical times and temperatures.

After exposure, the specimens were abraded to remove oxidation and four Rockwell C hardness measurements were taken in each of the specimens. The results are given in Table 24 and graphically in Figure 46.

These results show no difference in aging rates between stressed and unstressed mill annealed Rene' 41. The specimens were subjected to a uniaxial stress whereas a restrained weldment in Rene' 41 sheet has biaxial residual stresses. However, this test is more severe in that no stress relief could take place during the exposure time.

4.0 Effect of Grain Size on the Strain-Age Crack Susceptibility of Rene' 41

Work reported in Phase I of this report indicated that grain size may have a potent effect on crack susceptibility. This effect is indicated in Figure 47 where two heats of Rene' 41, with nearly identical chemical

TABLE 24

MILL ANNEALED TENSILE PROPERTIES OF RENE' 41 HEAT 2495-8182

Testing Temperature (°F)	TS Kpsi	.2% YS Kpsi	.02% YS Kpsi	% Elongation
RT	146	75.9	62.3	52
RT	149	79.3	63.0	50
RT	145	74.5	59.4	53

ROCKWELL C HARDNESS VERSUS AGING PARAMETERS FOR STRESSED AND UNSTRESSED RENE' 41

Aging Temperature (°F)	1100			1200		1300			1400		
Aging Time (hours)	1	16	30	1	16	1	16	30	1	16	29
Parameter (C = 20)	31.2	33.1	33.5	33.2	35.2	35.5	37.4	37.8	37.2	39.4	40.0
Hardness (Rockwell C) Zero Stress	23.3	27.9	28.3	31.7	33.7	32.0	38.7	37.6	38.6	42.4	46.3
Hardness (Rockwell C) 62.6 Kpsi Stress	20.0	27.5	28.3	31.2	34.6	31.9	38.3	38.8	38.7	42.6	43.1

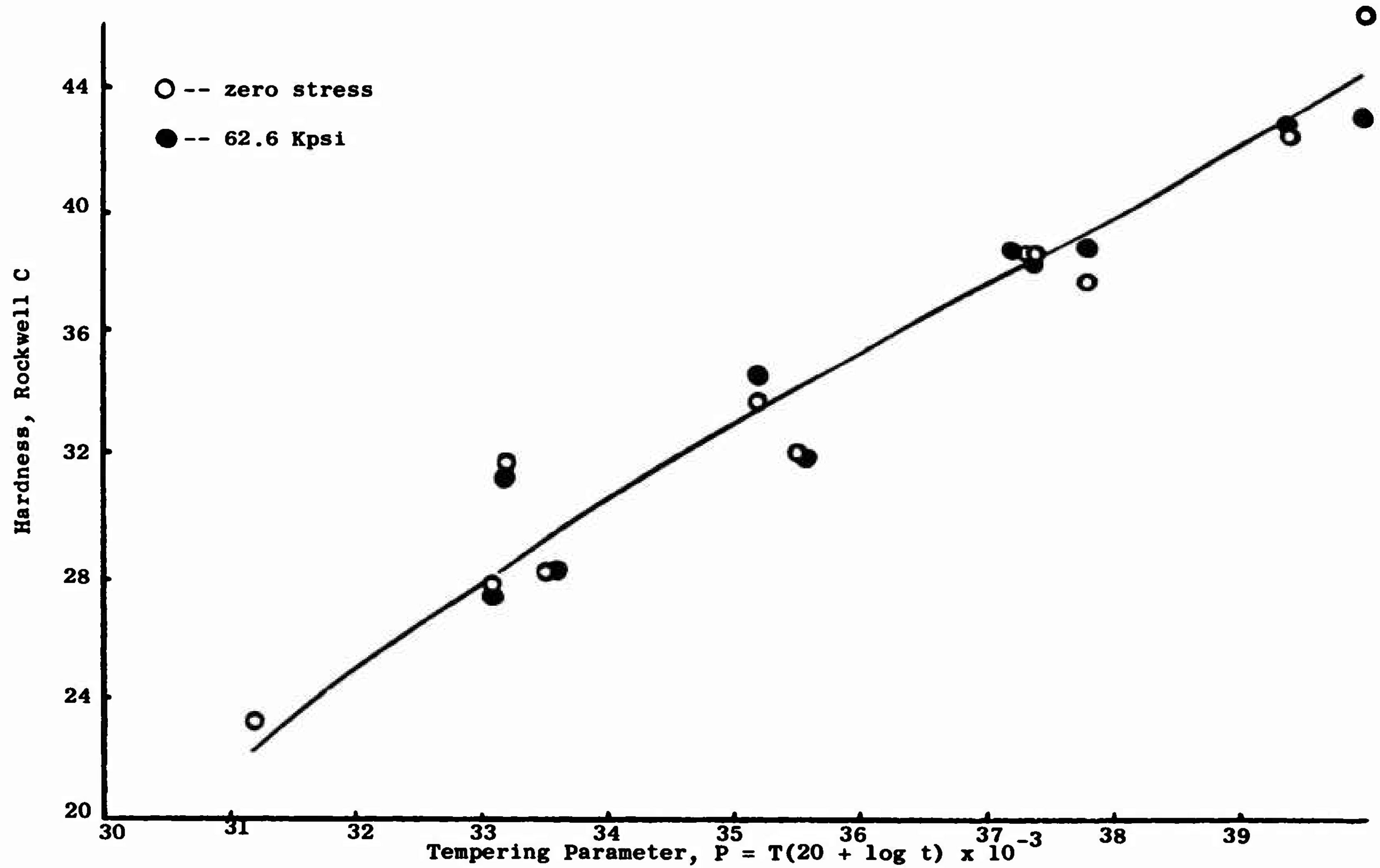


FIGURE 46. Aging Response of Rene' 41 In The Presence of Stress.

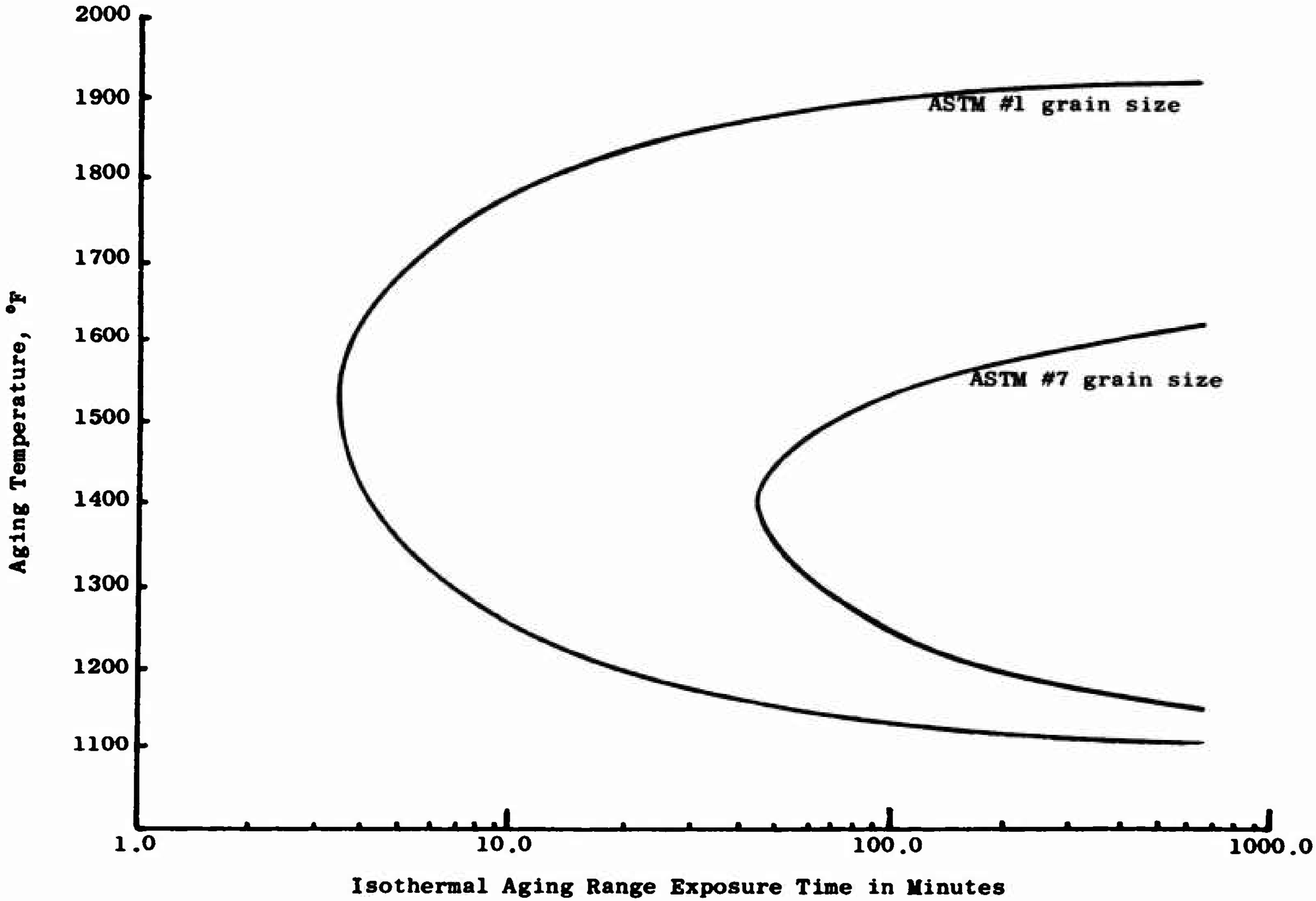


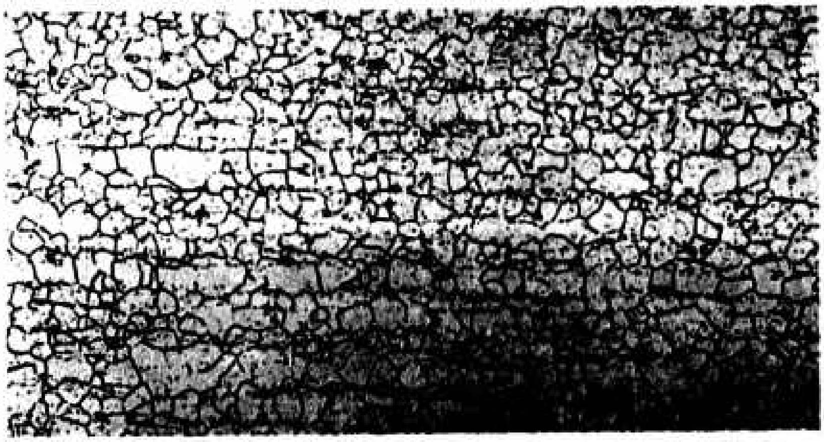
FIGURE 47. Comparison of the Crack Susceptibility of Two Heats of Rene' 41 With Different Mill Annealed Grain Sizes. C-Curves Generated With the Patch Test Using the Type III Post Weld Heat Treatment for Rene' 41 Heat Number 11 (grain size ASTM #1) and Experimental Heat Number 10 (grain size ASTM #7).

composition but widely differing grain sizes (ASTM 1 versus ASTM 7) also exhibited significant differences in sensitivity to strain-age cracking. In an attempt to further define the effect of grain size on strain-age crack sensitivity, the following work was conducted.

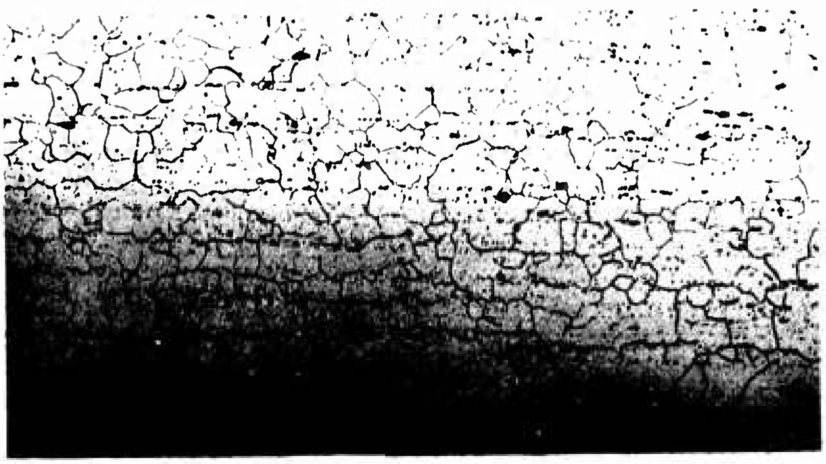
It was known that grains could be grown by solutioning Rene' 41 at 2150°F rather than 1975°F, but this solutioning temperature simultaneously produced other microstructural changes which may affect weldability; namely, complete solutioning of the M_6C carbides which does not occur at 1975°F. Grains can also be grown in superalloys by preceding the solutioning with a critical amount of cold work. This critical cold work produces exaggerated grain growth during the subsequent anneal.

To determine the critical cold work, 1 inch by 6 inch coupons of 0.060 inch Rene' 41 were cold rolled 4.2%, 6.7%, 10%, 15%, and 20%, then annealed at 1950°F. The resultant microstructures are shown in Figure 48. From these results, 4.2% appeared to be the critical amount of work. Several sheets of Rene' 41 were cold rolled 4.2%, followed by an anneal at 1950°F/10 minutes, AC. The material was evaluated for weldability using the constant strain "Gleeble" testing procedure described in Phase II. The results are given in Table 25.

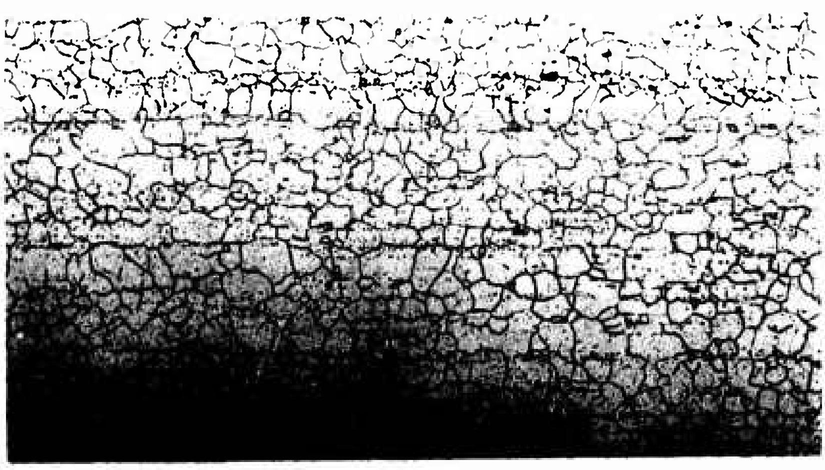
An identical procedure for increasing grain size was used for 0.025 inch thick Rene' 41 Heat Number 11. It resulted in grain growth from ASTM 8 to ASTM 3. The resultant material was evaluated for weldability and the results are given in Table 26. These results exhibited no difference in susceptibility to strain-age cracking over the range of ASTM 8 to ASTM 3.



0% Cold Work
Grain Size: ASTM 6



4.2% Cold Work
Grain Size: ASTM 3



6.7% Cold Work
Grain Size: ASTM 6

FIGURE 48. Effect of Cold Work Prior to Solutioning on Resultant Grain Size.
Rene' 41 Heat 5384

Neg. Nos. N8177
N8178
N8179

Mag: 100 X
Etch: HCl and HNO_3

TABLE 25

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41
HEAT 5384 SHOWING THE EFFECT OF GRAIN SIZE

Grain Size (ASTM #)	Test Temperature °F	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
6	1300	.0557	84.1	45	HAZ
3	1300	.0426	82.7	45+	DNF
6	1300	.148	101.5	FOL	weld
3	1300	.0794	103	FOL	PM/weld
6	1500	.0377	70.0	45+	DNF
3	1500	.0361	70.0	45	HAZ/weld
6	1500	.0542	85.6	45	HAZ
3	1500	.0561	82.1	46	HAZ
6	1700	.125	40.0	FOL	PM/HAZ
3	1700	.0484	44.6	45.0	weld
6	1700	.0577	39.3	45+	DNF
3	1700	.0606	39.2	45.0	HAZ/weld

Legend

DNF - did not fail
HAZ - heat affected zone
PM - parent metal
FOL - failed on loading

Notes on Testing Procedure

1. Consistent Peak Initial Stress and Strain applied to each specimen.

2. Specimen Design: See Figure 20.

TABLE 26

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41

HEAT NUMBER 5384 SHOWING THE EFFECT OF GRAIN SIZE

Grain Size (ASTM #)	Test Temperature °F	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
8	1300	.148	101.5	FOL	weld metal
3	1300	.0426	82.7	45+	DNF
3	1300	.0794	103	FOL	PM
8	1500	.0542	85.6	<45	HAZ
3	1500	.0361	70.0	<45	HAZ
3	1500	.0561	82.1	46	HAZ
8	1700	.0577	39.3	45+	DNF
3	1700	.0484	44.6	<45	weld metal
3	1700	.0606	39.2	<45	HAZ

Legend

DNF - did not fail
HAZ - heat affected zone
PM - parent metal
FOL - failed on loading

Notes on Testing Procedure

1) Consistent Peak Initial Stress and Strain applied to each specimen.

2) Specimen Design: See Figure 20.

5.0 Effect of Base Metal Thickness on Susceptibility of Rene' 41 to Strain-Age Cracking

During the first year's work[1], patch testing showed that restrained weldments in 1/4 inch thick plate were more susceptible to strain-age cracking than were weldments in 0.060 inch thick sheet. This was attributed to the higher restraint present in the thicker material.

In the present effort, the comparative weldability of 0.025 inch thick and 0.060 inch thick Rene' 41 was determined. Rene' 41 Production Heat Number 11 was cold rolled from 0.060 inch to 0.025 inch then annealed at 1950°F/ 10 minutes and water quenched. The microstructure after a solution and age is shown in Figure 49. The 0.060 inch and 0.025 inch thick sheet were evaluated for weldability using the constant strain "Gleeble" test described in Phase I. The results are shown in Table 27. The grain size of the two thicknesses of material is also included in Table 27.

These results show that the fine grained, thin Rene' 41 was more resistant to strain-age cracking than the coarse grained thick Rene' 41.

6.0 Effect of Post Weld Heat Treating Environment on Strain-Age Crack Sensitivity in Rene' 41

Recent work at Rocketdyne (Division of North American Rockwell[3]) has shown a marked decrease in incidence of strain-age cracking in welded Rene' 41 by use of a protective environment, rather than air, during post weld heat treatment. Their weldability evaluations were performed using a circular patch test in nominally 1/4 inch thick plate.

To determine the extent of improvement which could be gained in 0.060 inch thick welded Rene' 41 sheet by post weld heat treating in a protec-

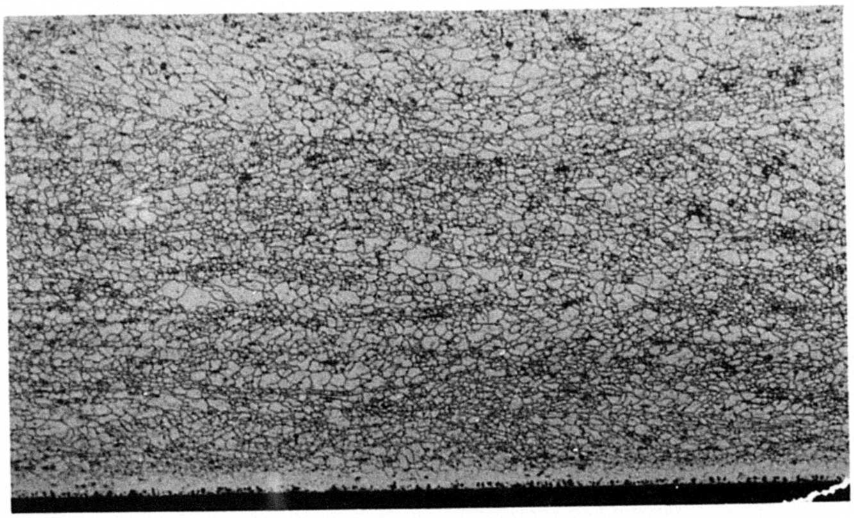


FIGURE 49. General Structure of Rene' 41 Heat Number 11. Cold Rolled from 0.060 Inch to 0.025 Inch. Annealed 1950°F for 10 Minutes, Water Quenched, Solutioned 1975°F for ½ Hour, Air Cooled, Aged 16 Hours at 1400°F.

Neg. No. N9126

Mag: 100 X
Etch: HCl and HNO_3

TABLE 27

RESULTS OF CONSTANT STRAIN GLEEBLE TESTING RENE' 41 HEAT 11 SHOWING THE EFFECT OF BASE METAL THICKNESS AND GRAIN SIZE

Material Thickness (inches)	Grain Size ASTM No.	Test Temperature (°F)	Specimen Elongation (inches)	Peak Initial Stress(ksi)	Time to Failure (min)	Failure Location
.060	1	1300	.0316	58.5	46.5	PM/HAZ
.025	8	1300	.0393	58.6	45+	DNF
.025	8	1300	.0313	64.0	45	Weld
.060	1	1500	.0355	61.4	1.2	PM
.025	8	1500	.0484	61.3	45	HAZ
.025	8	1500	.0361	68.2	45+	DNF
.060	1	1700	.0338	39.6	45	PM
.025	8	1700	.135	31.1	FOL	PM
.025	8	1700	.0341	11.7	30+	DNF

Legend:

FOL - Failed on loading.
DNF - Did not fail
HAZ - Heat affected zone
PM - Parent metal

Notes on Testing Procedure:

1) Consistent peak initial stress or strain applied to each specimen.
2) Specimen design: Figure 20.

tive environment, both patch testing and constant strain "Gleeble" testing were conducted. Patch testing was performed in vacuum and in air using the Type III heat treating procedure described in Phase I of this report. The vacuum heat treatment was conducted in an all metal cold wall vacuum furnace. A maximum pressure of one micron (10^{-3} Torr) was maintained. The comparative effects of vacuum and air heat treating environments on strain-age crack susceptibility are shown in Figures 50 and 51 for two production heats of Rene' 41. These results show a distinct improvement above 1500°F.

Testing in the "Gleeble" apparatus was performed in vacuum, air, and argon using two heats of 0.060 inch thick Rene' 41. The constant strain "Gleeble" testing procedure is described in Phase II. The test results are given in Table 28. These results also show an advantage of the protective atmosphere above 1500°F, but no advantage at the lower temperatures. These results, thus indicate that the improvement afforded by a protective environment during post weld heat treatment is at the higher temperatures.

7.0 Effect of Welding Process on the Strain-Age Crack Susceptibility of Welded Rene' 41

During the first year's work[1], patch testing showed a marked improvement in strain-age crack resistance of electron beam weldments over gas tungsten-arc (TIG) weldments. The C-curve comparing the two processes was developed using the Type I post weld heat treating procedure and is shown in Figure 52.

TIG and electron beam welded specimens were subjected to "Gleeble" evaluation using both the constant load and constant strain testing procedure as defined in Phase I. Production Heats Number 11 and 5384 in the mill

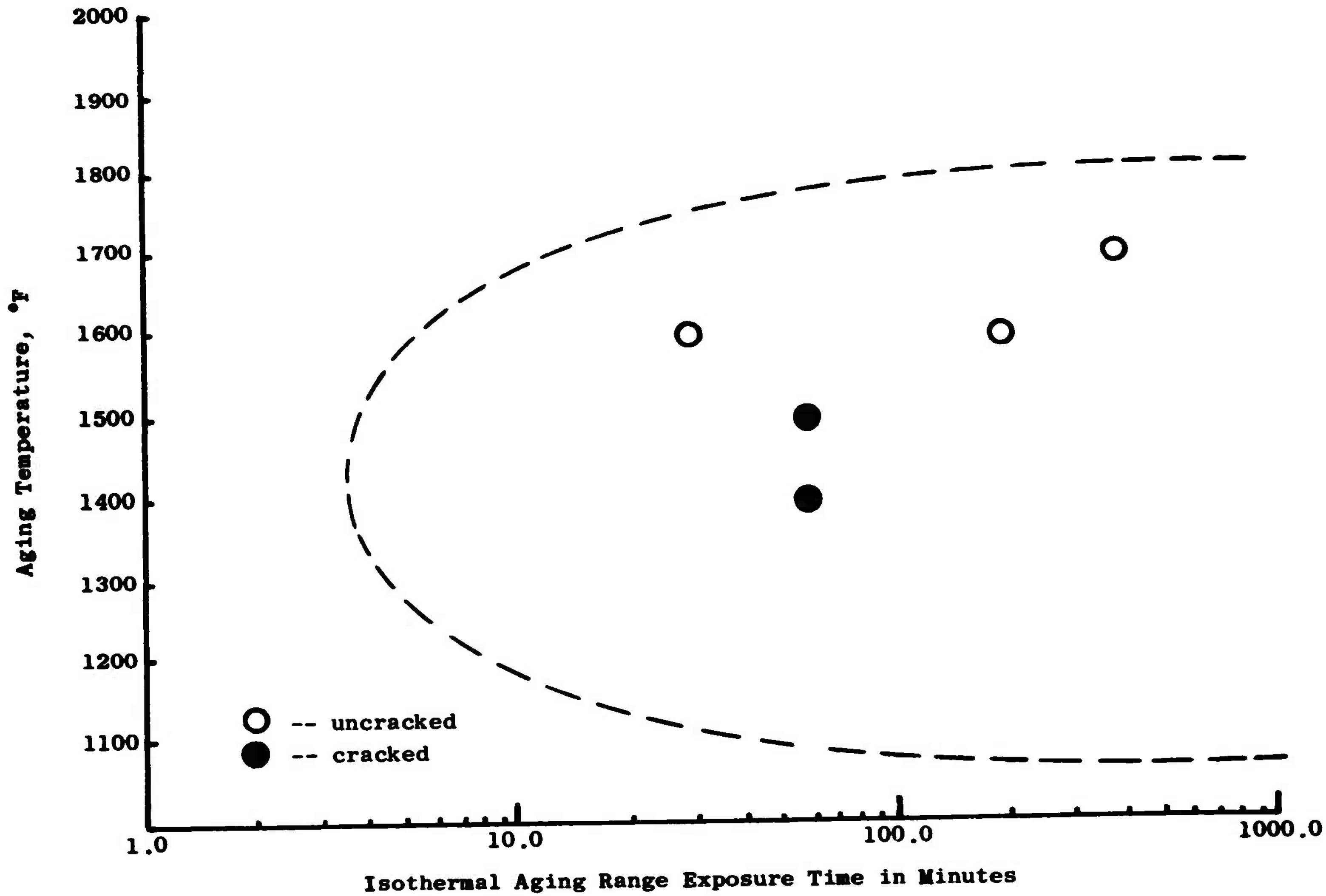


FIGURE 50. Effect of Post Weld Heat Treating in Vacuum on Strain-Age Cracking Susceptibility. Crack Susceptibility Determined by the Patch Test Using the Type III Post Weld Heat Treatment. Rene' 41 Heat Number 11. Mill Annealed Prior to Welding. The dotted C-curve was generated for this heat in an air heat treating environment.

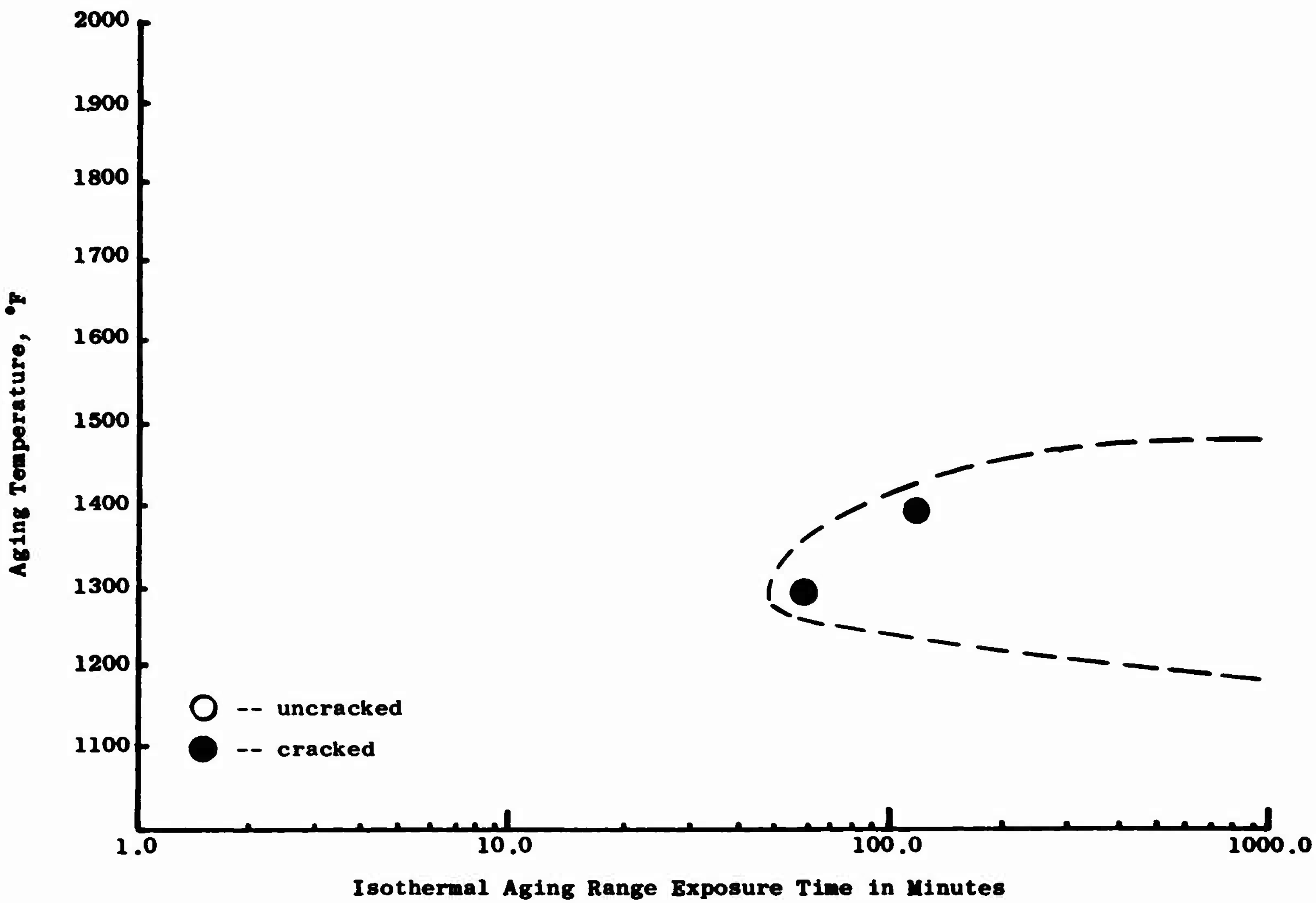


FIGURE 51. Effect of Post Weld Heat Treating in Vacuum on Strain-Age Cracking Susceptibility. Crack Susceptibility Determined by the Patch Test Using the Type III Post Weld Heat Treatment. Rene' 41 Heat 5384. Mill Annealed Prior to Welding. The dotted curve was generated for this heat using an air heat treating environment.

TABLE 28

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41

SHOWING THE EFFECT OF TESTING ENVIRONMENT

Heat Number	Testing Environment	Test Temperature °F	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
43	argon	1400	.069	79.8	45+	DNF
43	air	1400	.0581	78.8	45+	DNF
11	vacuum	1400	.020	61.0	3	HAZ
11	argon	1400	.0202	58.7	4	HAZ
11	air	1400	.020	45.6	1.3	HAZ
43	argon	1500	.0529	70.0	<45	HAZ/PM
43	air	1500	.0407	70.0	45+	DNF
11	vacuum	1500	.0193	37.9	FOL	HAZ
11	argon	1500	.0173	44.8	FOL	HAZ
11	air	1500	.0198	43.8	5	HAZ
43	argon	1600	.0448	59.0	<45	PM/HAZ
43	air	1600	.0603	57.7	<45	PM/HAZ
11	vacuum	1600	.0203	40.4	<45	HAZ
11	argon	1600	.0205	44.4	2.4	HAZ
11	air	1600	.012	32.1	FOL	HAZ
43	argon	1700	.0845	40.4	FOL	HAZ
43	air	1700	.083	43.4	FOL	PM
11	vacuum	1700	.0198	41.8	<45	HAZ
11	argon	1700	.020	36.0	<45	HAZ
11	air	1700	.0193	29.8	FOL	HAZ

Legend

FOL - failed on loading
DNF - did not fail
HAZ - heat affected zone
PM - parent metal

Notes on Testing Procedure

1. Consistent Peak Initial Stress and Strain applied to each specimen.

2. Specimen Design: Heat Number 43 -- See Figure 20.
Heat Number 11 -- See Figure 16.

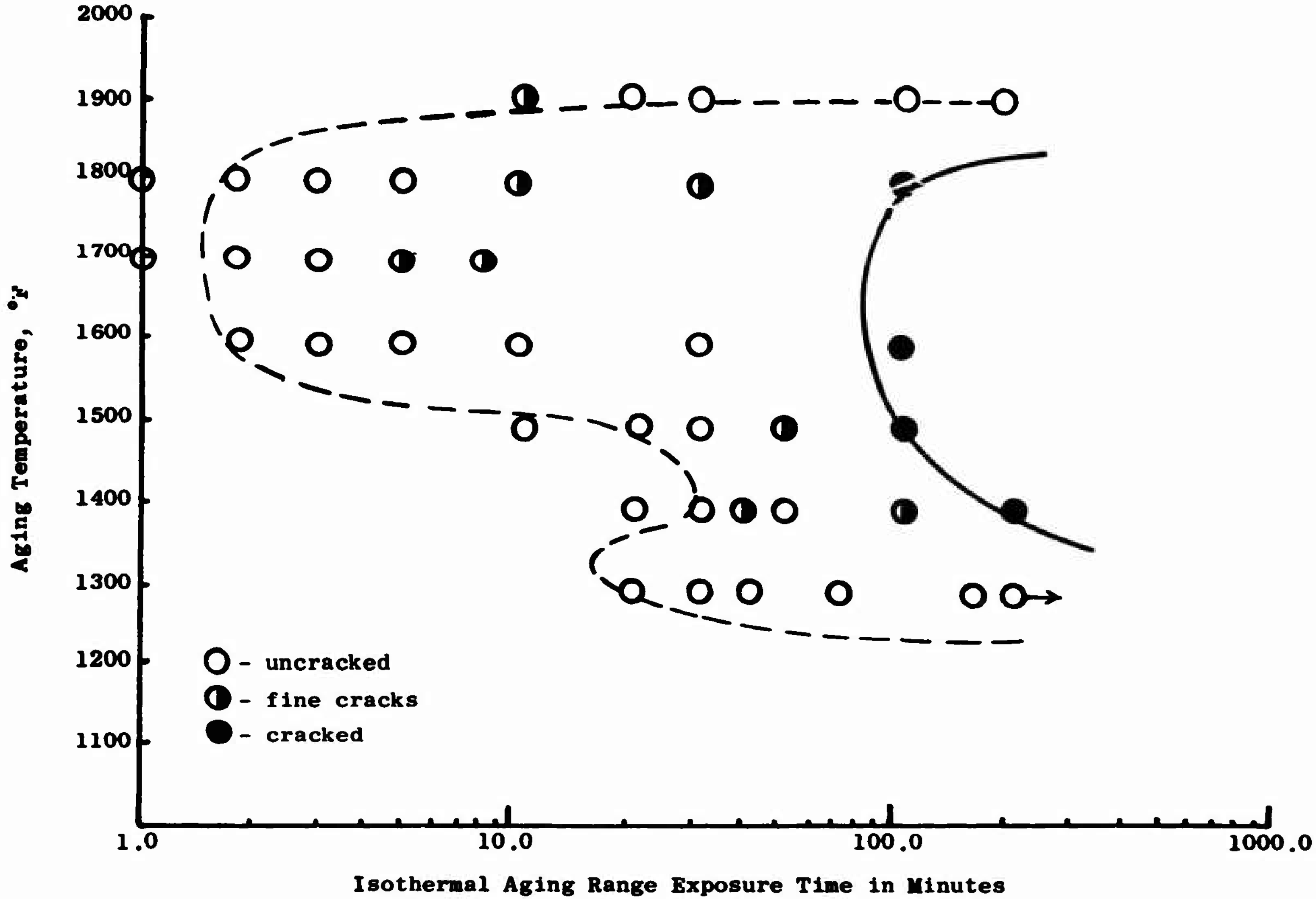


FIGURE 52. Crack Susceptibility C-Curve As Generated by the Patch Test Using The Type I Post Weld Heat Treatment. Heat Number T3-8565 Welded by the Electron Beam Process. The dotted line was generated by patch testing TIG welded Rene' 41 Heat Number T3-8565.

annealed condition were used. The results are given in Tables 29 and 30 and in Figure 53 for the constant load test procedure. The results of the constant strain "Gleeble" testing procedure are given in Table 31. TIG and electron beam welded specimen failure times were nearly identical, thus indicating that in the presence of identical stresses, there is little difference between the sensitivity of TIG and electron beam weldments to strain-age cracking.

8.0 Conclusions of Phase II Results

1) An overaging heat treatment prior to welding was, by far, the most effective method of reducing the incidence of strain-age cracking. The mechanical properties of overaged Rene' 41 can be completely restored by a post weld solution and aging heat treatment.

2) Rene' 41 with a mill annealed grain size of ASTM 3 to 8 was demonstrated to possess a greater resistance to strain-age cracking than Rene' 41 with a mill annealed grain size of ASTM 1.

3) The trend, established during the first year's effort, which indicated that Rene' 41 with low levels of iron, silicon, sulfur, and manganese had greater resistance to strain-age cracking was confirmed.

4) Lowering the carbon content of Rene' 41 also increases the resistance to strain-age cracking. However, a method of restricting grain growth in low carbon Rene' 41 must be developed if the room temperature to 1400°F yield strength

is to be retained at current specification levels.

5) The use of a vacuum during post weld heat treatment was found to increase the resistance of Rene' 41 to strain-age cracking at temperatures above 1500°F.

6) Welding processes which lower the residual stress level will reduce the sensitivity of the weldment to strain-age cracking.

TABLE 29

"GLEEBLE" TEST RESULTS, CONSTANT LOAD TEST PROCEDURE ELECTRON BEAM WELDED SPECIMENS

RENE' 41 HEAT NUMBER 11 IN THE MILL ANNEALED CONDITION

Isothermal Aging Temperature	Reference Stress Level (Kpsi)	Percentage of Reference Stress (%)	Applied Stress (Kpsi)	Time to Failure (min)	Time-Temperature Parameter $T(20 + \log t) \times 10^{-3}$
1330	102.0	40	40.9	22.3	35.0
1425	106.0	40	42.5	14.7	36.6
1520	92.3	40	37.0	30.3	39.0
1610	77.0	40	30.8	12.3	40.0
1700	60.0	40	24.0	30.3	42.5
1820	40.3	40	16.1	1.7	42.0
1925	20.6	40	8.3	21.3	46.6
1330	102.0	50	51.0	4.5	33.8
1415	106.0	50	53.0	15.0	36.4
1510	92.3	50	46.1	4.5	37.2
1650	77.0	50	38.5	.96	38.4
1700	60.0	50	30.0	1.02	39.4
1810	40.3	50	20.1	14.6	43.9
1925	20.6	50	10.3	4.6	45.0
1320	102.0	60	61.2	14.0	34.1
1410	106.0	60	63.6	.7	33.6
1520	92.3	60	55.4	.47	35.0
1610	77.0	60	46.2	.45	36.7
1700	60.0	60	36.0	1.76	39.9
1810	40.3	60	24.2	1.97	41.8
1910	20.6	60	12.4	1.84	43.6

Specimen Design: See Figure 16.

TABLE 30

"GLEEBLE" TEST RESULTS, CONSTANT LOAD TEST PROCEDURE. TIG WELD SPECIMENS. RENE' 41 HEAT 11 IN THE MILL ANNEALED CONDITION

Isothermal Aging Temperature	Reference Stress Level (Kpsi)	Percentage of Reference Stress (%)	Applied Stress (Kpsi)	Time to Failure (Min)	Time - Temperature Parameter $T(20+\log t) \times 10^{-3}$
1310	102.0	40	40.9	137.0	35.8
1410	106.0	40	42.5	27.2	36.8
1525	92.3	40	37.0	3.1	37.2
1605	77.0	40	30.8	0.6	37.2
1700	60.0	40	24.0	14.2	43.3
1800	40.3	40	16.1	40.9	44.8
1910	20.6	40	8.3	14.3	45.9
1320	102.0	50	51.0	10.5	34.3
1410	106.0	50	53.0	3.2	35.0
1525	92.3	50	46.1	13.3	38.4
1620	77.0	50	38.5	0.3	36.8
1700	60.0	50	30.0	14.2	41.8
1825	40.3	50	20.1	6.0	43.4
1910	20.6	50	10.3	13.3	45.8
1310	102.0	60	61.2	8.0	33.8
1425	106.0	60	63.6	1.1	34.2
1520	92.3	60	55.4	1.0	36.0
1620	77.0	60	46.2	.7	37.6
1700	60.0	60	36.0	.65	38.9
1840	40.3	60	24.2	1.5	42.3
1915	20.6	60	12.4	3.3	44.5
1320	102.0	70	71.4	3.0	33.3
1400	106.0	70	74.2	.8	33.6
1520	92.3	70	64.6	.4	35.2
1600	77.0	70	53.8	.3	36.6
1700	60.0	70	-	-	-
1820	40.3	70	28.2	1.7	42.1
1925	20.6	70	14.4	5.0	45.1

NOTE: Specimen is shown in Figure 16.

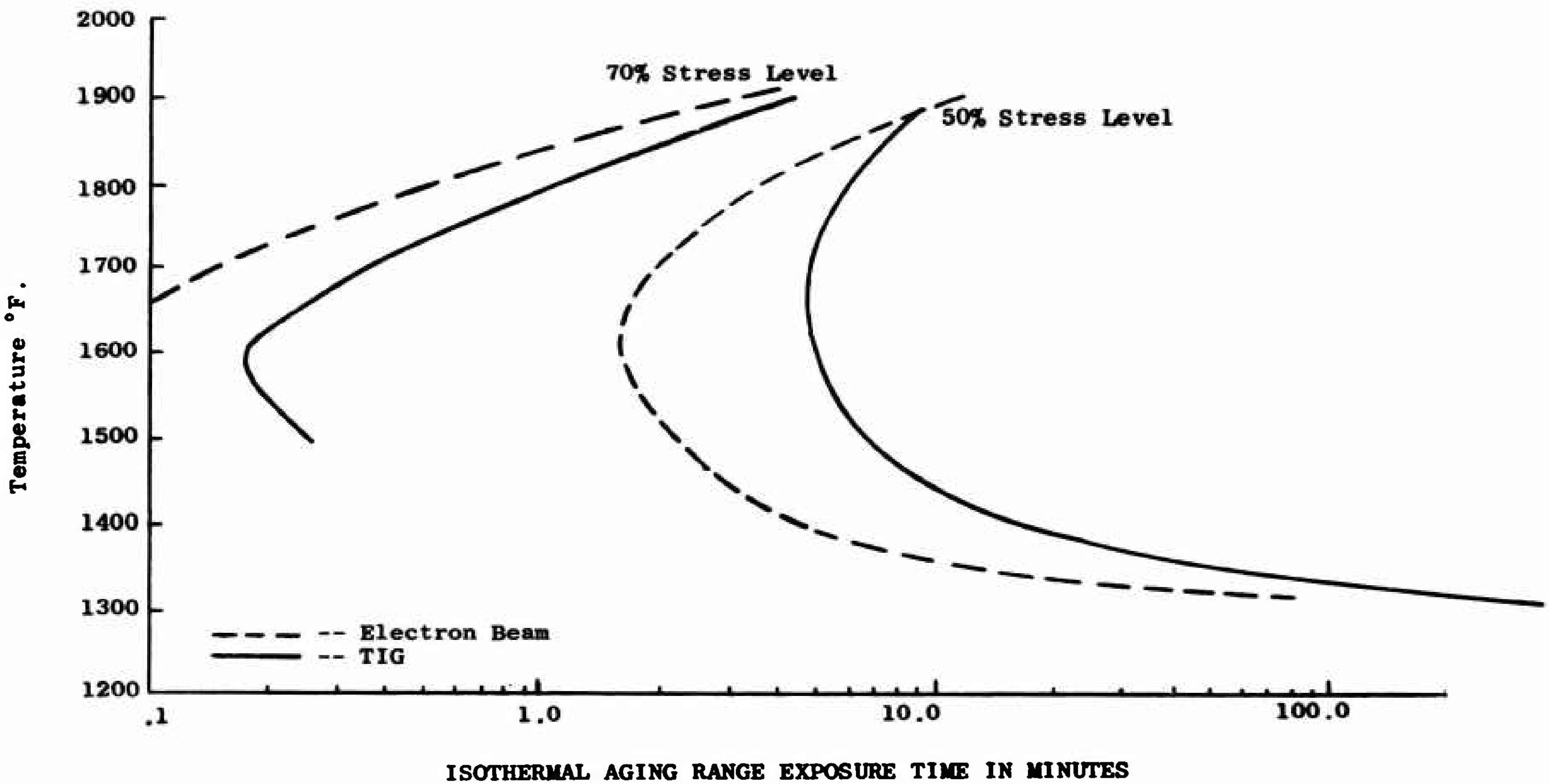


FIGURE 53. Crack Susceptibility C-Curve As Generated By the Gleeble Using the Constant Load Test Procedure. Rene' 41 Heat Number 11. Specimen Design Shown in Figure 16. Results Tabulated in Tables 29 and 30.

TABLE 31

RESULTS OF CONSTANT STRAIN GLEEBLE TESTING RENE' 41 HEAT 5384 SHOWING THE EFFECT OF WELDING PROCESS ON STRAIN-AGE CRACK SUSCEPTIBILITY

Welding Process	Test Temperature (°F)	Specimen Elongation (inches)	Peak Initial Stress(ksi)	Time to Failure (min)	Failure Location
TIG	1300	.0557	84.1	<45	HAZ
EB	1300	.0535	82.2	45+	DNF
TIG	1300	.148	101.5	FOL	Weld
EB	1300	.197	105	FOL	PM
TIG	1500	.0377	70.0	45+	DNF
EB	1500	.0475	74.5	45+	DNF
TIG	1500	.0542	85.6	<45	HAZ
EB	1590	.0542	82.4	<45	HAZ
TIG	1700	.125	40.0	FOL	PM/HAZ
EB	1700	.184	41.0	FOL	Weld
TIG	1700	.0577	39.3	45+	DNF
EB	1700	.060	40.7	45+	DNF

Legend:

TIG = Gas tungsten-arc welding process
EB - Electron beam welding process
FOL - Failed on loading
DNF - Did not fail
HAZ - Heat affected zone
PM - Parent metal

Notes on Testing Procedure:

1) Consistant peak initial stress or strain applied to each specimen.
2) Specimen design: Figure 20.

C. PHASE III

SPECIFICATION VERIFICATION

1.0 Introduction

Based on the conclusions of Phase II, a sheet of Rene' 41 was procured from a 5,000 pound heat with the modifications which were shown to improve resistance to strain-age cracking while maintaining acceptable mechanical properties. The testing in this phase of the program served to substantiate on a production size heat what had been tentatively concluded for laboratory size heats of Rene' 41. The Rene' 41 so selected was high purity (low iron, silicon, sulfur, and manganese) and fine grained. The other chemical constituents were maintained identical to those in Experimental Heat Number 10 since it provided high resistance to strain-age cracking.

2.0 Evaluation of Production Heat of Rene' 41 with High Resistance to Strain-Age Cracking

The chemical composition, grain size, mechanical and metallurgical properties of the Rene' 41 (Allvac Heat 5384) from the 5,000 pound heat are listed in Tables 14, 15, 16, and 17. In all aspects they exceeded the minimum requirements required in General Electric's Rene' 41 Specification. The microstructure was shown previously in Figure 37.

2.1 Determination of the Strain-Age Crack Susceptibility in the Mill Annealed Condition

The Production Heat 5384 was evaluated for weldability in the mill annealed condition using the Type III patch test procedure and the constant strain "Gleeble" test procedure.

The patch test results are presented in Figure 54. The C-curve compares favorably with the C-curve of the crack resistant Experimental Heat Number 10, thereby indicating no problem in scaling up to a production size heat.

The constant strain "Gleeble" test results are presented in Table 32 compared with the results of Experimental Heat Number 10. Again, the results are comparable indicating no difference in weldability between the experimental and production size heats.

2.2 Strain-Age Crack Susceptibility of Rene' 41 in the Overaged Preweld Heat Treated Condition

The response of the production size heat of Rene' 41 to overaging prior to welding was evaluated using both the patch test and "Gleeble" test procedure.

The results of the patch testing are shown in Figure 55. The "Gleeble" test results are given in Table 32. The patch tests verified the conclusions from Phase II -- that strain-age cracking in a welded patch test could be eliminated through use of an overaging preweld heat treatment. The "Gleeble" test results were less conclusive but indicated a reduction in the strain-age crack susceptibility by overaging prior to welding.

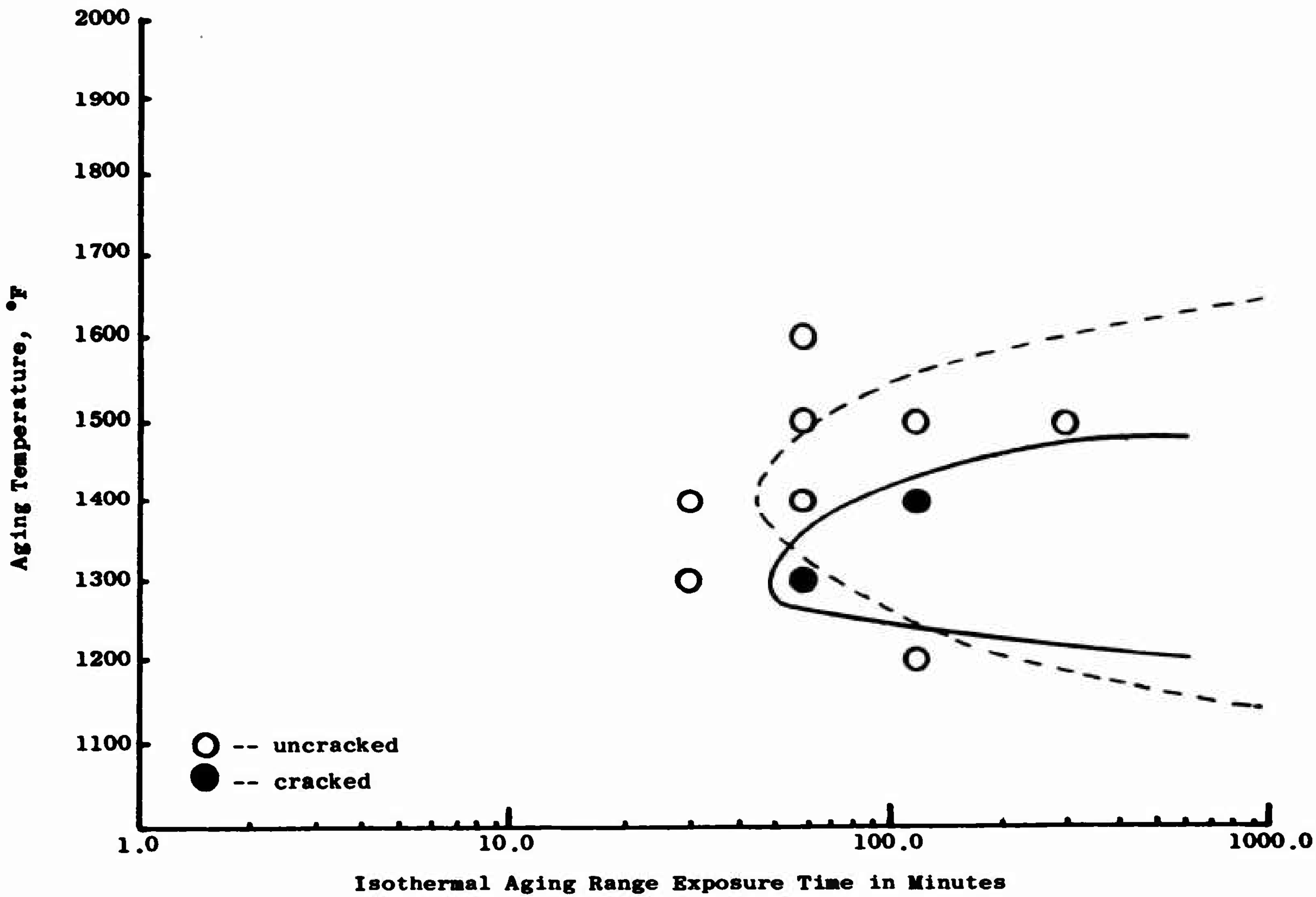


FIGURE 54. Crack Susceptibility C-Curve As Generated By the Patch Test Using the Type III Post Weld Heat Treatment. Rene' 41 Heat 5384, Mill Annealed Prior to Welding. The dotted C-curve is that of Experimental Heat Number 10.

TABLE 32

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41 SHOWING THE EFFECT OF PREWELD HEAT TREATMENT ON STRAIN-AGE CRACK SUSCEPTIBILITY

Heat Number	Preweld Heat Treatment	Test Temperature °F	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	MA	1300	.154	81.1	4	PM
5384	MA	1300	.0557	84.1	<45	HAZ
5384	OA	1300	.0426	82.0	45+	DNF
5384	MA	1300	.148	101.5	FOL	weld
5384	OA	1300	.0929	105.0	FOL	weld
10	MA	1500	.0534	69.4	<45	HAZ
5384	MA	1500	.0377	70.0	45+	DNF
5384	OA	1500	.0613	70.0	<45	HAZ
5384	MA	1500	.0542	85.6	<45	HAZ
5384	OA	1500	.0547	69.7	45+	DNF
10	MA	1700	.058	44.1	11	
5384	MA	1700	.125	40.0	FOL	PM/HAZ
5384	OA	1700	.133	39.2	FOL	PM
5384	MA	1700	.0577	39.3	45+	DNF
5384	OA	1700	.0587	34.6	45+	DNF

Legend

MA - mill annealed (1950°F/ 10 minutes, water quench
OA - overaged
DNF - did not fail
HAZ - heat affected zone
PM - parent metal

Notes on Testing Procedure

1) Consistent Peak Initial Stress and Strain applied to each specimen.

2) Specimen Design: See Figure 20.

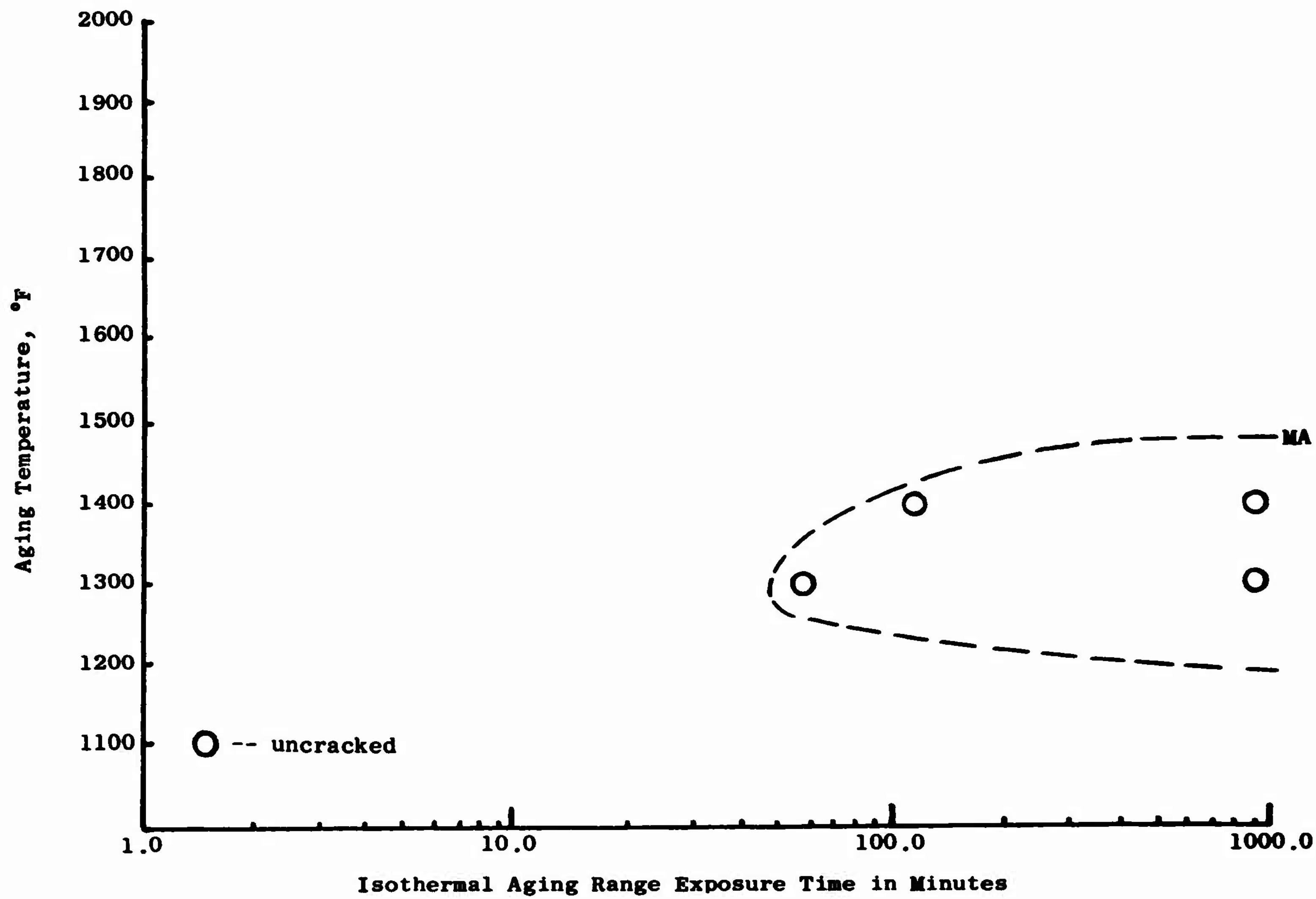


FIGURE 55. Effect of Overaged Preweld Heat Treatment. Determined by the Patch Test Using the Type III Post Weld Heat Treatment. Rene' 41 Heat 5384. The dotted C-curve is that of Heat 5384, mill annealed prior to welding.

The mechanical property evaluation conducted in Phase II on overaged Rene' 41 (Heat 5384) shows that the properties can be completely restored by solutioning and aging.

3.0 Conclusion of Phase III Results

These results confirm that high purity (low iron, silicon, sulfur, and manganese), fine grained Rene' 41 is resistant to strain-age cracking. The results also confirmed the ability of the overage preweld heat treatment to eliminate cracking in a production size heat of Rene' 41.

D. PHASE IV

ADDITIONAL NICKEL BASE SUPERALLOYS

The weldability evaluation (constant strain "Gleeble" procedure) developed for Rene' 41 was extended to another high strength nickel base superalloy, Rene' 63, as follows.

A heat of Rene' 63 (Number 96172) was selected for evaluation. Its chemical composition is shown here.

C	Cr	Co	Mo	W	Al	Ti	B	Ni
.076	13.78	14.80	6.16	3.09	3.70	2.37	.014	Bal

The weldability of this alloy was varied by the preweld heat treatment as follows:

1) Annealed 10 minutes at 2050°F and water quenched. Material in this condition could be TIG or electron beam welded into patch tests and successfully heat treated but could not be repair welded without cracking. This material was considered to have poor weldability.

2) Annealed 10 minutes at 2050°F, furnace cooled (35 to 40°F/hour) to 1900°F, slow cooled to room temperature, heated to 1900°F for 10 minutes and water quenched. TIG and electron beam welded patch test assemblies fabricated from this material could be heat treated, repair welded, and heat treated without cracking. This material was considered to have good weldability.

Sheets of material with both degrees of weldability (as measured by patch testing) were subjected to the constant strain "Gleeble" testing procedure as described in Phase I. The results are given in Table 33.

Three conclusions are immediately apparent from these results. The "Gleeble" test was useful in rating strain-age crack sensitivity in other nickel base superalloys. The strain capacity of the Rene' 63 was much less than that of Rene' 41 indicating greater sensitivity to strain-age cracking. This corresponds with the patch test data, i.e., Rene' 63 is more sensitive to strain-age cracking than Rene' 41. Secondly, the data indicate very little difference between the Rene' 63 in the two preweld conditions.

A critical review of the patch test data indicated a distinct difference in weldability between the two heats of Rene' 63 with respect to cracking <u>during</u> cooling from the post weld heat treatment and cracking during repair welding. There was not evidence of marked differences in crack sensitivity <u>during heating</u> to the post weld solutioning temperature. The "Gleeble" test procedure is sensitive specifically to the on-heating cracking.

TABLE 33

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING

RENE' 63

Preweld Condition	Test Temperature (°F)	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
Rene' 41 (#10)	1300	.154	81.1	4	PM
crack sensitive	1300	.0393	82.3	45+	DNF
crack resistant	1300	.0442	82.4	25	PM/HAZ
crack sensitive	1300	.1290	127.6	FOL	PM
crack resistant	1300	.0923	128.0	FOL	PM/HAZ
Rene' 41 (#10)	1500	.0534	69.4	<45	HAZ
crack sensitive	1500	.0390	70.6	45+	DNF
crack resistant	1500	.0413	71.0	1.5	PM/HAZ
crack sensitive	1500	.0477	123.7	FOL	PM
crack resistant	1500	.040	69.3	FOL	PM/HAZ/weld
Rene' 41 (#10)	1700	.058	44.1	11	--
crack sensitive	1700	.0772	44.9	<45	PM
crack resistant	1700	.0335	44.6	<45	HAZ
crack sensitive	1700	.0632	33.4	<45	PM
crack resistant	1700	.0674	48.4	FOL	

Legend

FOL - failed on loading
DNF - did not fail
HAZ - heat affected zone
PM - parent metal

Notes on Testing Procedure

1) Consistent Peak Initial Stress or Strain applied to each specimen.

2) Specimen Design: See Figure 20.

IV. DISCUSSION OF RESULTS

The results of the first year's effort and the information reported herein make it possible to postulate a detailed model of the strain-age cracking mechanism in nickel-base alloys. For strain-age cracking to occur, two conditions are required:

1) A highly restrained component which maintains a high level of residual welding stress during subsequent exposure to aging temperatures.

2) An alloy which is age hardenable and has a low capacity for stress relaxation.

It can be hypothesized that strain-age cracking occurs as a result of the summation of:

1) Residual welding stresses are a function of the welding process, weld filler metal, joint design, and base metal thickness. These stresses are primarily those generated by weld metal contraction during and following solidification modified by whatever geometric stress concentration factors are present.

2) Aging contraction stresses (which are a function of base metal chemistry and heat treatment).

3) Thermal stresses imposed during heat treatment.

4) Stress relaxation during heat treatment.

The cumulative total of these stresses are imposed on the heat affected zone (HAZ) region adjacent to the fusion line which, during welding, was virtually completely solutioned. During subsequent aging temperature range exposure, carbide precipitation (most often identified as $M_{23}C_6$) occurs preferentially at the HAZ grain boundaries thus resulting in low ductility in this region. Minor impurity elements also tend to segregate at grain boundaries and reduce ductility. In a restrained weldment, the stresses are relieved by relaxation during heat treatment. When the strain associated relaxation exceeds the strain capacity of the "embrittled" heat affected zone, cracking ensues.

An analysis of this cracking mechanism indicates that sensitivity to strain-age cracking can be reduced either by lowering the cumulative stress level acting on the heat affected zone or by increasing the strain capacity of this zone.

A critical examination of the results and conclusions of this study can be made to indicate how each of these support the above model. For convenience of the reader, the most significant conclusions are repeated below.

1) A restrained weld "patch" test post weld heat treating procedure (named Type III) was developed which quantitatively measured the time to initiate strain-age cracking occurring during an isothermal arrest in the aging temperature range for precipitation hardened nickel base alloys.

2) Two "Gleeble" test procedures, a constant strain and a constant load, were also developed which could measure differences in strain-age cracking sensitivity.

3) For quantitative measurement of differences in strain-age cracking susceptibility, the constant load "Gleeble" test procedure is the simplest and fastest testing procedure developed. Its simplicity makes it adaptable to other test equipments and would allow a more widespread usage of this procedure as a strain-age crack susceptibility test.

4) The C-curve using the patch test Type III post weld heat treating procedure which defines the isothermal exposure areas which are subject to strain-age cracking, can be used to select the minimum heating rate to the solution treatment temperature for a highly restrained weldment to avoid strain-age cracking.

5) An overaging heat treatment prior to welding was, by far, the most effective method of reducing the incidence of strain-age cracking. The mechanical properties of overaged Rene' 41 can be completely restored by a post weld solution and aging heat treatment.

6) Rene' 41 with a mill annealed grain size of ASTM 3 to 8 was demonstrated to posses a greater resistance to strain-age cracking than Rene' 41 with a mill annealed grain size of ASTM 1.

7) The trend, established during the first year's effort, which indicated that Rene' 41 with low levels of iron, silicon, sulfur, and manganese had greater resistance to strain-age cracking, was confirmed.

8) Lowering the carbon content of Rene' 41 also increases the resistance to strain-age cracking. However, a method of restricting grain growth in low carbon Rene' 41 must be developed if the room temperature to 1400°F yield strength is to be retained at current specification levels.

9) The use of a vacuum during post weld heat treatment was found to increase the resistance of Rene' 41 to strain-age cracking at temperatures above 1500°F.

10) Welding processes which lower the residual stress level will reduce the sensitivity of the weldment to strain-age cracking.

The restrained circular patch test was found to be invaluable in this study. This test device was representative of a weldment in which the summation of residual stresses could be maximized. Through studies utilizing the patch test, it was found the strain-age cracking could occur during an isothermal arrest in the aging temperature range (Type III) upon rapid cooling from such an exposure (Type I) or from a slow cool from the exposure condition if a significant amount of aging could occur during the cooling period (Type II). The cracking "C-curves" determined during the isothermal arrest provided the most valuable information since, once generated, they provided a basis for selection of a minimum continuous heating rate which could be used to avoid cracking.

The two "Gleeble" procedures developed provided more economical methods for measuring differences in strain-age crack sensitivity. Of these two tests, the constant load test is simpler and could conceivably be conducted with conventional stress-rupture equipment if attention and care are exercised in obtaining similar heating rates. This would allow more widespread usage of this procedure as a weldability test.

Other investigators[4, 5] have also successfully correlated cracking during stress relaxation in a test specimen with sensitivity of the alloy to strain-age cracking. In these works, specimens with simulated heat affected zones were used rather than welded specimens. The simulated heat affected zone was prepared by rapid heating to a temperature very close to the melting temperature of the alloy. Biaxiality in the specimens was required and was accomplished with a machined notch.

Biaxiality in the welded specimens is also required for the two "Gleeble" test procedures. The face reduced specimen design (Figure 1b) is recommended for the constant load procedure because it promotes failure in the heat affected region. The 45° welded specimen (Figure 20) is recommended for the constant strain procedure so that larger and more controllable amounts of strain can be applied.

Any strain-age crack susceptibility study conducted in the future cannot be effectively performed using any one of these tests alone. Any study in which the effects of changes in welding parameters are to be investigated can only be accurately studied using the patch test. This test is capable of measuring differences in restraint and/or residual stress applied by different welding processes. It was documented in this work that gas tungsten-arc and electron beam welding processes produce the same results when tested on the "Gleeble", but a wide difference in crack susceptibility between welds produced by these two processes was measured with the patch test. This was attributed to the differences in residual stresses applied to the patch test by these processes. Preweld heat treatment which changes either the strain capacity of the heat affected zone or the parent metal can be studied by either of the test procedures.

The decreased strain-age cracking sensitivity of higher purity material (low iron, silicon, and manganese) is attributed to an increase in the strain capacity in the heat affected zone. The metallurgical nature of this increase in ductility was not identified. The trend toward improvement in strain-age crack resistance with lower carbon content is associated with a reduction in the amount of $M_{23}C_6$ carbide which is precipitated in this zone.

An overaging treatment prior to welding improves resistance to strain-age cracking by allowing the parent metal to remain weak and ductile (relative to the HAZ) while the heat affected zone, through aging, becomes strong and less ductile during the post weld heat treatment. The stress relaxation is forced to occur in the weaker, more ductile voluminous base metal.

Fully aged or mill annealed parent metal prior to welding is not effective in reducing strain-age cracking sensitivity because the heat affected zone never becomes as strong as the parent metal -- thus, stress relaxation must occur in the HAZ which does not have sufficient strain capacity for the reason mentioned above.

The reason(s) for the grain size effect can only be conjectured because the thermomechanical processing history which produced the large grain size is unknown, but it is understandable that large grain size reduces the amount of grain boundary area. Reactions which prefer grain boundaries would be concentrated in this smaller area, and therefore, these boundaries would become embrittled to a greater degree.

The basic mechanism which operates in a low oxygen content environment which reduces the incidence of strain-age cracking at temperatures above 1500°F is unknown. It is not unreasonable to attribute the greater cracking tendency in air to the higher rate of oxidation at these temperatures. The preferred mode of oxidation is along grain boundaries. This oxidation mechanism would be expected to be embrittling. The basic mechanism is to be explored in depth at Rocketdyne (Division of North American Rockwell). Although the use of a protective atmosphere did not help in the more critical lower temperature region of the C-curve, it would be of assistance to lower the upper region of the C-curve so that during continuous heating of welded components, particularly more massive parts, this area could be more easily avoided.

The results generated under this contract have provided valuable information pertaining to the strain-age cracking mechanism. Valuable tools were developed which will be useful in the application of welding processes to sheet alloys which possess higher elevated temperature strength than Rene' 41. These tools should also be valuable to research programs directed toward a further understanding of the mechanism of strain-age cracking.

V. REFERENCES

1) Hughes, WP; Berry, TF; and Yount, RE - "A Study of the Strain-Age Crack Sensitivity of Rene' 41" - Technical Report AFML-TR-66-324; September, 1966.

2) Private Communication; Marble, JD; Mechanical Metallurgist, Materials Development Laboratory, Aircraft Engine Technology Division, General Electric Company.

3) Prager, M and Thompson, EG - " A Study of the Mechanical Properties and Strain-Age Cracking of Rene' 41 for F-1 Rocket Engine Applications" - Rocketdyne Report R-7111; September, 1967.

4) Murray, JD - "Stress Relief Cracking in Carbon and Low Alloy Steels" - British Welding Journal; August, 1967.

5) Wu, KC and Herfert, RE - "Microstructural Studies of Rene' 41 Simulated Weld Heat Affected Zones" - Welding Journal, 46 (1), Research Supplement, 32-S to 38-S (1967).

VI. RECOMMENDATIONS FOR FUTURE STUDY

1) The strong influence of an overaging treatment to increase the sensitivity of Rene' 41 to strain-age cracking should be studied on other nickel base precipitation hardened alloys. One serious limitation to the application of other sheet alloys with higher elevated temperature mechanical properties than those of Rene' 41 has been their weldability. One major limitation has been their extreme sensitivity to strain-age cracking. The improvement in resistance to strain-age cracking by a preweld overaging heat treatment in such sheet alloys as Rene' 63, Astroloy, (or U-700) and a recently developed alloy under Air Force sponsorship at Universal Cyclops AF2-IDA should be documented.

2) The selected overaging treatment examined for improvement in crack sensitivity was capable of moving the C-curve of the alloy to the right by several orders of magnitude. The improvement measured far exceeds that which is required in the production of Rene' 41 welded components. Other overaging treatments should be explored to develop the most economical overaging treatment with respect to a desired shift in the crack susceptibility C-curve.

3) Demonstrate the effectiveness of the constant load "Gleeble" testing technique using more conventional test equipment. The "Gleeble", for the constant load procedure, provides the advantage of rapid heating to the desired isothermal exposure temperature. The procedure could be

duplicated in a stress rupture station if a rapid heating technique can be applied. A preheated clam-shell furnace or an induction heated susceptor could be utilized.

4) Investigate the potential of varying the thermomechanical processing sequence for Rene' 41 to produce and maintain a fine grain sized low carbon, high purity (low iron, silicon, sulfur, and manganese) material. Document the effect of this alloy composition and structure for decreasing the strain-age crack sensitivity of Rene' 41.

A P P E N D I X   A

WELDING PROCEDURE FOR THE PATCH TEST ASSEMBLY

Appendix A

Welding Procedure for the Patch Test Assembly

1) The inner center disc, outer restraining sheet and heavy base plate were machined as shown in Figure 1. The pieces were machined such that the gap between the center disc and the outer restraining was 0.025". The outer restraining sheet was machined such that a pressfit existed between the outer restraining sheet and the heavy base plate.

2) All surfaces and edges to be welded were thoroughly cleaned with an 80 grit belt sander and wiped off with acetone.

3) The outer restraining disk was fusion tacked (no filler) to the base plate. The center restraining disk was automatically gas tungsten arc welded to the heavy base plate using the following parameters:

Filler Material - Hastelloy W, 0.045" diameter

Current - 70-80 amps

Voltage - 8 volts

Wire Feed - 16 1/2 ipm

Joint Travel Speed - 10 ipm

Gas Coverage - argon, 12-15 cfh

Gas Backing - argon, 5-10 cfh

4) The rootside of the weld performed in 3, was wire brushed and gas tungsten-arc welded with a washing or blending pass in which the heat from the torch was concentrated on the heavy base plate. The parameters

used for this operation were as follows:

Filler Material - Hastelloy W, 0.045" diameter

Current - 60-70 amps

Voltage - 8 volts

Wire Feed - 16 1/2 ipm

Joint Travel Speed - 10 ipm

Gas Coverage - argon, 12-15 cfh

Gas Backing - argon, 5-10 cfh

5) The center disk was tacked in four places to the outer restraining sheet. The tacks were made such that they were nearly flush to the surface of sheet. Joint gaps ranged from 0.040"-0.050". The center disk was welded from the crownside orientation of the outer restraining weld to obtain 100% penetration on a single pass. The following parameters were used:

Filler Material - Hastelloy W, 0.045" diameter

Current - 55 amps

Voltage - 8 volts

Wire Feed - 16 1/2 ipm

Joint Travel Speed - 7 ipm

Gas Coverage - 12-15 cfh

Gas Backing - 8-15 cfh

6) The completed patch test assembly was fluorescent penetrant inspected.

7) Composition of Hastellow W filler metal:

Element	Weight %
Ni	62
Mo	24.5
Cr	5
Fe	5.5

APPENDIX B

GENERAL ELECTRIC SPECIFICATION FOR RENE' 41

1. SCOPE

1.1 General Electric Material Specification B50T59 identifies a nickel base alloy trademarked Rene'41 by the General Electric Company.

1.2 This specification contains the following classes:

B50T59A - Mill anneal at 1975F, Rapid Quench
B50T59B - Mill anneal at 1975F, Rapid Quench
B50T59C - B50T59A plus solutioning at 1975F for 30 minutes, air cool; plus aging at 1400F for 16 hours, air cool.
B50T59D - B50T59B plus solutioning at 2050F for 30 minutes, air cool; plus aging at 1650F for 4 hours, air cool.
B50T59E - Welding wire, cold drawn and solution treated at 2150F air, oil, or water quenched.

1.2.1 All temperatures refer to metal temperatures $\pm$ 25F. All times refer to time at temperature for the heaviest section.

* 1.3 All material supplied to this specification shall be produced by vacuum induction melting plus vacuum consumable electrode remelting.

1.4 The temperature of material during its final pass through the last roll on the hot rolling mill shall not exceed 2050F and "in process" annealing temperature shall not exceed 2000F.

2. CHEMICAL COMPOSITION %

2.1 Material supplied to this specification shall be of the following composition:

Carbon	0.12 Max.	Cobalt	10.00-12.00
Silicon	0.50 Max.	Molybdenum	9.00-10.50
Manganese	0.10 Max.	Titanium	3.00- 3.30
Iron	5.00 Max.	Aluminum	1.40- 1.60
Chromium	18.00-20.00	Nickel	Remainder
Boron	0.003-0.010		
Sulfur	0.015 Max.		

2.1.1 (a) For B50T59E only: Boron analyses on welding wire are not required.

(b) For sheet only: The Boron content as reported by the manufacturer per paragraph 2.2 shall be deemed sufficient. The Boron content need not conform to the requirements of paragraph 2.1 when analyzed by the purchaser.

2.2 The ladle or ingot analysis made by the manufacturer to determine the percentages of elements required by this specification shall conform to the requirements of paragraph 2.1 and shall be reported to the purchaser in a certificate of test herein specified.

2.3 An analysis may be made by the purchaser and the chemical composition thus determined shall conform to the requirements of this specification within the following permissible variations (over the maximum limit or under the minimum limit) for check analysis, otherwise, the material shall be subject to rejection.

Carbon	+ 0.01	Boron	+ 0.001
Silicon	+ 0.02		- 0.0004
Manganese	+ 0.02	Cobalt	± 0.15
Sulfur	+ 0.005	Molybdenum	± 0.15
Iron	+ 0.15	Titanium	± 0.05
Chromium	± 0.20	Aluminum	± 0.05

3. MECHANICAL PROPERTIES

3.1 For all tensile tests, a strain rate of 0.005 inch/inch/ minute maximum through the 0.2% yield strength shall be used. The head speed used from 0.2% yield strength to fracture shall be reported.

3.2 Machining source for tensile and stress rupture specimens must be approved by the appropriate Flight Propulsion Division Laboratory.

3.3 All sheet specimens shall be cut perpendicularly to the rolling direction and bar specimens shall be taken longitudinally from the centers of the bars.

* 3.3.1 Deleted.

3.4 Tensile Properties (ASTM E21-58T)

3.4.1 Deleted

3.4.1.1 Deleted

3.4.2 Material to B50T59A shall meet the following mechanical properties when solution treated and aged to B50T59C.

3.4.2.1 Tensile properties of sheet, strip, and plate at 1400F:

(1)	Tensile Strength, psi	
	Yield Strength (0.2% offset) psi	111,000
	Elongation (% in 2 inches) min.	3(0.027" & over)
(1)	Elongation (% in 2 inches)	(0.026" & under)

(1) Report values in certificate of test for information

3.4.2.2 Tensile properties of bar and forgings at 1400F;

(1)	Tensile Strength, psi ---------------------	
	Yield Strength (0.2% offset) psi ----------	111,000
	Elongation (% in 2 inches) minimum --------	5
	Reduction in Area %, minimum --------------	8
(1)	Report values in certificate of test for information	

3.4.3 Flash welded rings to B50T59A and B50T59B shall conform to AMS 7490 except welded rings shall be mill annealed at 1975F and oil or water quenched prior to proof testing of welds. After proof testing, rings shall again be mill annealed at 1975F and oil or water quenched.

3.4.3.1 Each weld lot (single run per part number) of flash welded rings to B50T59A and B50T59B shall be subject to the requirements of paragraph 4.2 of this specification and to the Technical Requirements of AMS 7490. The frequency of lot sampling and number of test samples per lot shall be determined by the appropriate AGT Quality Control Organization.

3.5 Stress Rupture Properties (ASTM E139-58T)

3.5.1 Material to B50T59B shall meet the following mechanical properties when solution treated and aged to B50T59D.

3.5.1.1 Bars, forgings, sheet, strip, and plate rupture specimen tested at 1650F and 25,000 psi must meet the following requirements:

Stock (Nominal)	Minimum Life (Hours)
.041 & Under	10
.042 - .050	15
.051 and Over	20

3.6 Hardness

3.6.1 The following hardness requirements shall be met at room temperature:

B50T59A and B50T59B	
Sheet and Strip (.070 & under)---------------	Rockwell C27 Max. or equiv.
Sheet and Strip (.071 to .187)---------------	Rockwell C30 Max. or equiv.
Plate, Bar, Forgings, & Flash Welded Rings --	321 Brinell Max. or equiv.
B50T59C -------------------------------------	Rockwell C35 Min.
B50T59D -------------------------------------	Rockwell C30 Min.
B50T59E -------------------------------------	Rockwell C30 Max. or equiv.

4. QUALITY

* 4.1 All material supplied to this specification shall be aircraft quality. Material shall be uniform in quality, clean, sound, and free from foreign materials and from internal and external imperfections detrimental to fabrication or to performance of parts.

4.2 Unless otherwise specified, sheet, strip, plate, bar, forgings, and flash welded rings (excluding weld) shall have an equiaxed grain structure with an average grain diameter of ASTM No. 3 or finer, as determined by comparison of a polished and etched specimen with the chart in ASTM E112.

4.3 Spooled wire shall be in one continuous length, level wound, free from kinks, waves, and bends. It shall be free to unwind without restriction caused by overlapping or wedging. The outside end shall be brought to the outside of the flange of the spool. Spool size shall be as specified on the purchase order.

4.4 Melted wire shall flow smoothly and evenly during welding and shall be capable of producing acceptable welds.

4.5 Metallographic Inspection

4.5.1 Total intergranular attack on sheet and strip supplied to this specification shall not extend to a depth greater than .0005 inch when determined at 500X minimum on unetched specimens.

4.6 Ultrasonic Inspection

4.6.1 All bar stock, plate, forgings and flash welded rings (excluding weld) shall meet the ultrasonic inspection requirements of P50T13A.

5. TOLERANCES

5.1 Sheet, strip, and plate: Unless otherwise specified tolerances of sheet, strip, and plate shall conform to the latest revision of AMS 2262 as applicable.

5.2 Bar: Unless otherwise specified, tolerances of bar shall conform to the latest revision of AMS 2261 as applicable.

5.3 Welding Wire: Welding wire shall be furnished on spools or in straight lengths as specified and shall not vary in length more than plus or minus 1/4 inch from the length ordered.

5.3.1 Unless otherwise specified, the diameter of the wire shall not vary more than plus or minus 0.002 inch from the size ordered.

5.4 Forgings: All tolerances shall be agreed on by the vendor and the appropriate FPD Engineering Group, or in accordance with applicable drawings.

6. CERTIFICATE OF TEST

6.1 The material manufacturer must certify all of the chemical and mechanical tests herein specified. The manufacturer shall furnish with each shipment three copies of a certificate of test showing the numerical results of tests for chemical composition of each heat in the shipment and the numerical results of all other required tests for each thickness of sheet, strip, and plate and for each size bar from each heat. The certificate shall show that the results are in accordance with the requirements of this specification and shall be mailed by the manufacturer to the purchaser with or preceding the shipment of the material.

6.2 The certificate of test shall also contain the following information:

(a) Requisition number
(b) Heat number
(c) Sizes and quantities
(d) Specification class and revision number
(e) Testing source for tensile and stress rupture specimens
(f) The head speed from 0.2% yield to fracture.

7. MARKING

7.1 Sheet, Strip, and Plate

7.1.1 Each sheet, flat strip, and plate over 6 inches in width shall be marked with a continuous pattern of this specification and revision number in stenciling on one side of each piece. Flat strip 6 inches wide and less shall be similarly marked on each end, and all coil strip shall be similarly marked on the outside end of each coil. In addition, each sheet, strip, and plate shall be marked with the heat number and the nominal thickness. The characters shall not be less than 3/8 inch in height and shall be applied using a suitable marking fluid. The marking shall have no deleterious effect on the material or its performance. The marking fluid shall be sufficiently stable to withstand ordinary handling, but shall be capable of being removed in hot alkaline cleaning solution without rubbing.

7.2 Bar

7.2.1 Each bar shall be stamped with the specification number and revision number or corresponding stock serial code. All bar stock bundles shall have the identifying requisition number, heat number, and specification and revision number clearly marked on the outside with a suitable tag.

7.3 Welding Wire

7.3.1 Each bundle or container shall be legibly marked with the purchase order number, wire diameter, net weight, manufacturer's name, heat number, and this specification and revision number. If spools of wire are supplied, each spool shall be legibly and semi-permanently identified on one flange with the preceding information.

7.4 Forgings

7.4.1 All forgings shall be marked in accordance with the latest revision of AMS 2808.

8. PACKING

8.1 All material shall be packed to prevent damage or loss in shipment, and shall be separated by size and heat number. Each shipment shall be identified with the purchase order number, manufacturer's name, this G-E specification and revision number, sizes and heat numbers.

(S1)	Issue		10-13-58
(S2)	Issue	(ECN 30405)	11-16-59
(S2)	Issue	(ECN 30288)	11-16-59
(S2)	Issue	(ECN 30301)	11-16-59
(S2)	Issue	(ECN 30301-1)	11-16-59
(S2)	Issue	(ECN 30445)	11-16-59
	Amend.	I (CIDN 70750)	11-30-60
(S3)	Issue	(CIDN 71081)	3-15-62
	Amend.	I (CIDN 71200)	5-25-62
(S4)	Issue	(CIDN 71352)	1-10-63
	Amend.	I (CIDN 71541)	6- 7-63
(S5)	Issue	(CIDN 71918)	9-10-64
	Amend.	I (CID 72156)	12-22-65
	Amend.	II (CID 72188)	7-8-66
	Amend.	III (CID 72228)	10-14-66
S6	(CID 72337)		12-12-66

*Denotes latest change.

S-1 S-5
S-2 S-6
S-3 S-7
S-4

J.F.BARKER
M-76

APPENDIX C

MILL PROCESSING PROCEDURE USED TO ROLL EXPERIMENTAL HEATS OF RENE' 41 TO 0.060 INCH SHEET

1) Fifteen pound ingots of each heat were vacuum induction melted using virgin starting materials.

2) Each ingot was soaked 4 hours at 2125°F.

3) Initial ingot breakdown consisted of 1/4 inch reduction per pass with two passes per heating. Starting temperature 2100°F down to 1850°F finishing temperature. Ingots were reduced to 1 1/2 inches thick, rolling in the longitudinal direction of the billet. The slab was trimmed and inspected for cracking which yielded a slab 3 inches by 1 1/2 inches by approximately 18 inches long.

4) The slabs were cut into 6 inch long sections (6 inches by 3 inches by 1 1/2 inches) and cross rolled with 1 pass per heat using 1/16 inch reductions. The slab temperature was 2050 to 2075°F. The slabs were cross rolled to 6 inch width thus yielding a plate 6 inches by 6 inches by approximately 1/2 inch.

5) The slab was turned 90° and rolled in the longitudinal direction from 1/2 inch down to 1/4 inch with 0.040 inch reduction per pass p
The slab temperature was 2035 to 2050°F.

6) Hot rolling continued using 1 pass per heating, a temperature of 2035 to 2050°F, and the following reductions:

0.030 inch reductions from 1/4 inch down to 0.185 inch

0.020 inch reductions from 0.185 inch down to 0.145 inch

0.010 inch reductions from 0.145 inch down to 0.090 inch

7) The 0.090 inch sheet was annealed 10 minutes at 1975°F, water quenched, and descaled.

8) The sheet was cold rolled in 1 to 4 passes from 0.090 inch to 0.078 inch, annealed as above, and descaled.

9) Finish cold rolled in 4 to 5 passes from 0.078 inch to 0.060 inch and annealed.

10) The sheet was then roller leveled.

APPENDIX D

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

The following tables present the results of constant strain "Gleeble" testing Rene' 41 heats with variations in chemical composition.

The specimen design in shown in Figure 20. The testing procedure consisted of applying a peak initial strain to each specimen in Tables C1 through C6. A peak initial stress was applied to each specimen in Tables C7 through C12.

The abbreviations used in each table are:

FOL - failed on loading

DNF - did not fail

HAZ - heat affected zone

PM - parent metal

TABLE D1

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1200°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.175	84.1	<45	HAZ
23	.174	85.2	45+	DNF
24	.175	73.6	45+	DNF
25	.174	79.4	<45	PM
26	.175	90.9	14.5	PM
27	.184	84.6	36	PM
28	.1765	69.4	45+	DNF
29	.178	75.6	<45	PM/HAZ
30	.1775	90.0	<45	PM/HAZ
32	.176	97.3	<48	HAZ/PM
33	.177	81.5	45+	DNF
34	.1765	94.9	<45	PM
35	.1765	76.2	<45	HAZ/PM
36	.175	73.8	45+	DNF
37	.177	72.7	45+	DNF
40	.176	77.3	45+	DNF
42	.1765	90.4	<45	PM
39	.176	56.6	<45	HAZ

TABLE D2

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1300°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.154	81.1	4	PM
23	.208	91.2	13.7	PM
24	.206	79.4	$<$45	PM
25	.208	81.9	3.8	PM
26	.204	109.0	2.5	PM
27	.2075	85.2		
28	.2065	80.0	22.5	PM
29	.205	83.0	22.6	
30	.208	93.5	3.3	PM/HAZ
32	.206	106.0	13	HAZ/PM
33	.206	89.7	12	HAZ/PM
34	.213	106.0	1	PM
36	.205	83.3	16	PM
37	.208	76.5	$<$45	PM
38	.209	94.4	19	PM
40	.165	82.4	FOL	PM
42	.204	94.3	6.6	PM
39	.205	54.4	$<$45	HAZ/PM

TABLE D3

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1400°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.044	79.0	3	HAZ
23	.0455	68.5	21	HAZ
24	.0445	56.6	45+	DNF
25	.0457	61.4	<45	HAZ
26	.0438	65.8	45+	DNF
27	.0439	64.7	<45	HAZ
28	.0442	56.3	<45	weld
29	.0455	61.5	45+	DNF
30	.0445	68.2	<45	PM
32	.0432	79.1	45+	DNF
33	.0438	67.5	45+	DNF
34	.0426	74.4	45+	DNF
35	.0448	55.3	45+	DNF
36	.0438	62.5	45+	DNF
37	.0464	59.0	45+	DNF
38	.0441	68.4	45+	DNF
40	.0445	64.1	43+	DNF
42	.0445	77.2	37	-
39	.0445	35.8	45+	DNF

TABLE D4

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1500°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.0534	69.4	<45	HAZ
23	.0529	77.8	<45	HAZ
24	.0547	69.5	45+	DNF
25	.0553	71.3	6	HAZ
26	.0540	80.6	<45	PM
27	.0548	74.5	<45	PM
28	.0541	65.2	<45	HAZ
29	.0548	69.0	<45	PM
30	.0552	63.0	<45	PM/HAZ
32	.0548	84.1	<45	PM/HAZ
33	.052	78.8	<45	HAZ/PM
34	.0532	87.8	<45	HAZ/PM
36	.0538	70.3	<45	HAZ
37	.0539	62.4	<45	HAZ
38	.0529	79.8	<45	PM
40	.0556	68.1	33	HAZ
42	.0555	78.8	<45	PM
39	.054	32.3	45+	DNF

TABLE D5

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41

HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1600°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.0414	57.3	<45	HAZ
23	.0414	46.3	<48	HAZ
24	.0419	54.8	<45	HAZ/PM
25	.044	54.7	<45	HAZ
26	.0424	63.6	<45	HAZ/PM
27	.0416	61.2	45+	DNF
28	.0445	58.5	<45	HAZ
29	.0419	59.0	45+	DNF
30	.0435	63.2	<45	PM/HAZ
32	.0426	59.3	45+	DNF
33	.0423	60.0	45+	DNF
34	.0419	62.1	<45	PM/HAZ
35	.0434	55.8	17	HAZ
37	.0426	56.9	<45	weld
38	.0408	53.7	45+	DNF
40	.0426	63.3	8.5	
42	.0408	57.4	<45	HAZ
39	.046	8.1	30+	DNF

TABLE D6

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41
HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1700°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.058	44.1	11	
23	.0646	35.3	<45	HAZ/PM
24	.0596	39.0	<45	HAZ
25	.061	39.4	FOL	HAZ
26	.058	42.1	FOL	HAZ
27	.060	56.5	<45	HAZ
28	.061	28.1	45+	DNF
29	.0587	31.2	25	HAZ
30	.0574	46.0	<45	HAZ
32	.059	40.2	<45	PM/HAZ
33	.059	38.7	<45	HAZ/PM
34	.058	41.4	<45	HAZ/PM
37	.0606	39.1	<42	PM/HAZ
40	.0594	34.7	FOL	
42	.059	41.4	<45	HAZ
39	.0598	13.6	<45	HAZ/PM

TABLE D7

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1200°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.175	84.1	<45	HAZ
23	.160	84.1	<45	PM
24	.330	83.4	<45	PM/HAZ
25	.235	83.4	<45	HAZ
26	.1394	84.4	<45	PM
27	.1894	84.5	45+	DNF
28	.341	83.8	<50	PM
29	.260	84.0	<45	PM/HAZ
30	.0845	84.3	45+	DNF
31	.220	84.9	<45	HAZ
32	.159	83.4	<45	HAZ/PM
33	.164	81.8	<45	PM
34	.0794	83.7	45+	DNF
35	.254	83.9	31.3	PM
36	.236	82.4	<45	HAZ/PM
37	.302	83.9	<45	HAZ/PM
38	.118	83.7	45+	DNF
40	.070	84.4	45+	DNF
42	.129	83.4	<45	HAZ
43	.129	84.5	<45	PM/HAZ
39	.360	67.8	FOL	--

TABLE D8

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41
HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1300°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.154	81.1	4	PM
23	.116	81.5	35.9	HAZ
24	.235	82.6	21.6	PM
25	.195	82.2	31	PM
26	.0453	78.0	45+	DNF
27	.129	82.8	22.9	PM
28	.263	82.1	9	PM
29	.205	82.0	21.3	PM
30	.0977	82.3	29.3	PM
31	.121	81.6	<45	PM/HAZ
32	.1085	82.5	45+	DNF
33	.132	81.0	<45	HAZ
34	.0529	81.9	45+	DNF
35	.180	82.5	30	PM
36	.157	81.6	32.4	HAZ
37	.230	82.5	32.6	PM
38	.1065	82.8	<45	HAZ
40	.157	81.1	16.3	PM/HAZ
42	.100	81.5	45+	DNF
43	.0934	82.1	<45	PM
39	.217	56.0	FOL	--

TABLE D9

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41

HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1400°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.044	79.0	3	HAZ
23	.0639	79.0	9	HAZ
24	.0631	79.5	45+	DNF
25	.1076	80.6	1.4	HAZ
26	.0483	78.8	45+	DNF
27	.0993	79.2	36.3	PM/HAZ
28	.153	78.5	9	PM
29	.0875	74.0	45+	DNF
30	.0445	78.2	$<$45	HAZ
31	.1065	80.4	30	PM
32	.0538	79.4	45+	DNF
33	.0715	78.8	25	HAZ
34	.0438	79.4	45+	DNF
35	.1095	79.0	3	HAZ
36	.123	79.3	17	PM
37	.154	77.7	9	PM
38	.0591	79.0	45+	DNF
40	.1010	78.0	21.4	
42	.062	79.5	45+	DNF
43	.069	79.8	$<$45	PM
39	.198	54.9	FOL	--

TABLE D10

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1500°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.0534	69.4	<45	HAZ
23	.0441	70.0	39	HAZ
24	.0768	71.0	45+	DNF
25	.0597	70.0	1	HAZ
26	.0408	69.8	45+	DNF
27	.0704	71.3	<45	HAZ
28	.0839	69.6	<45	PM
29	.0625	70.0	<45	PM
30	.0524	70.8	<45	PM
31	.0592	70.4	<45	PM
32	.0467	70.4	45+	DNF
33	.0445	69.7	<45	PM
34	.041	70.9	45+	DNF
35	.050	70.0	15	HAZ
36	.0935	52.6	FOL	HAZ
37	.0762	70.6	<45	HAZ
38	.0529	69.4	<45	PM
40	.0812	70.6	14	PM
42	.0445	70.7	45+	DNF
43	.0529	70.0	<45	HAZ/PM
39	.129	42.5	FOL	--

TABLE D11

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1600°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.0414	57.3	<45	HAZ
23	.0413	57.9	<45	HAZ
24	.0426	57.8	<45	HAZ
25	.0391	54.6	FOL	HAZ
26	.0402	57.7	27	HAZ
27	.0584	58.0	<45	HAZ/PM
28	.0534	57.8		HAZ/PM
29	.0408	58.0	<45	HAZ
30	.049	59.1	<45	PM/HAZ
31	.0529	58.3	<45	HAZ
32	.0428	57.6	45+	DNF
33	.0467	57.7	<45	HAZ
34	.038	57.5	45+	DNF
35	.0441	58.0	3.5	HAZ
36	.0424	58.4	45+	DNF
37	.0442	57.6	<45	PM
38	.0434	57.6	<45	HAZ
40	.0424	58.3	9	
42	.0405	59.0	45+	DNF
43	.0448	59.0	<45	HAZ/PM
39	.118	30.6	FOL	HAZ

TABLE D12

RESULTS OF CONSTANT STRAIN "GLEEBLE" TESTING RENE' 41 HEATS WITH VARIATIONS IN CHEMICAL COMPOSITION

Test Temperature: 1700°F

Heat Number	Specimen Elongation (inches)	Peak Initial Stress (ksi)	Time To Failure (min)	Failure Location
10	.058	44.1	11	
23	.0625	33.9	FOL	PM
24	.098	40.5	FOL	HAZ/PM/weld
25	.070	37.4	FOL	HAZ
26	.062	40.7	FOL	PM
27	.102	44.0	4	PM
28	.0735	35.4	FOL	HAZ
29	.0772	41.9	FOL	HAZ
30	.118	37.5	FOL	HAZ/PM
31	.0904	39.0	30	PM
32	.0858	44.7	<45	HAZ
33	.0455	15.4	FOL	PM
34	.0406	43.9	<45	PM
35	.0514	37.9	FOL	HAZ
36	.0614	43.0	<45	PM/HAZ
37	.106	42.1		PM/HAZ
38	.0448	44.1	45+	DNF
40	.0296	44.5	<45	
42	.0584	42.6	FOL	HAZ
43	.0845	40.4	FOL	HAZ
39	.1250	22.6	FOL	HAZ

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) General Electric Company Aircraft Engine Group - MDL Cincinnati, Ohio 45215	2a. REPORT SECURITY CLASSIFICATION unclassified 2b. GROUP NA
3. REPORT TITLE A Study of the Strain-Age Crack Sensitivity of Rene' 41	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report No. 2 August 1, 1966 to February 15, 1968	
5. AUTHOR(S) (Last name, first name, initial) Hughes, Warren P. Berry, Thomas F. Yount, Reed E.	
6. REPORT DATE May, 1968	7a. TOTAL NO. OF PAGES 7b. NO. OF REFS 5
8a. CONTRACT OR GRANT NO. AF33(615)-2717 b. PROJECT NO. 7351 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) N.A.
10. AVAILABILITY/LIMITATION NOTICES ~~This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Metals and Ceramics Division (MAM), Air Force Materials Laboratory, Wright-Patterson AFB, Ohio 45433.~~	
11. SUPPLEMENTARY NOTES N.A.	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

A program of research work directed toward the study of strain-age crack sensitivity of precipitation hardened nickel base alloys in sheet form was conducted and is described. The alloy chosen for the study was Rene' 41.

A post weld heat treating procedure was devised for a restrained circular welded patch test which defined the isothermal exposure times and temperatures in the aging range where strain-age cracking occurs.

Two testing procedures were developed, a constant load and a constant strain, using "Gleeble" equipment (a time-temperature-stress device).

Using the above testing procedures, it was found that a preweld overaging heat treatment eliminated the occurrence of strain-age cracking in the most crack-prone heat of 0.060" Rene' 41 sheet studied.

The following factors were also found to reduce the strain-age crack sensitivity of Rene' 41: (1) maintaining the iron, silicon, sulfur, and manganese content at low compositional levels; (2) maintaining a finer grain size in annealed sheet than ASTM 3 (

DD FORM 1 JAN 64 1473

Security Classification

Figure 4. Sample Document Data Control Form Front

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Rene' 41						
restrained circular patch testing						
"Gleeble" testing						
strain-age cracking						
gas tungsten arc welding						
electron beam welding						
heat treatment						
mechanical properties						
metallography						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ______________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ______________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ______________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Security Classification

Figure 5. Sample Document Data Control Form Back